LBNE Conceptual Design Report

Volume 5: A Liquid Argon Detector for LBNE

June 16, 2010

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1 Volume Introduction

1.1 Introduction to Long Baseline Neutrino Experiment

Blah blah about LBNE. This is common to all volumes. (This comes from Gina.)

1.2 Introduction to the Liquid Argon Detector

1.2.1 Liquid Argon Technology

The passage of neutrinos through liquid argon produces ionization electrons, and it is through the observation of these outgoing charged particles that a liquid argon detector can identify neutrino events. The extraction of physics results from neutrino experiments requires very low backgrounds, which in turn requires detectors that are both extremely massive **FIXME:** *to capture more interactions to increase statistics?* and capable of recording extensive information about a localized energy deposition. **FIXME:** *Add a sentence about how statistics figure in – i.e. why you need high statistics* Most interesting experiments are in the statistics-limited parameter space **FIXME:** *jargon alert!!! Will need to restate!*, where analyzing power is generally proportional to the square root of size, but directly **FIXME:** *or 'always'?* proportional to the ability to eliminate background.

Thus, a large-scale detector with millimeter spatial resolution **FIXME:** *how do we know 'millimeter' res is sufficient? Compare to existing.* and few percent energy resolution has the potential to open a new frontier in neutrino research.

The Liquid Argon Time Projection Chamber (LArTPC) is the most promising new technology under development to achieve the dual goals of massive size and high spatial and energy resolution. Although much work remains to be done, LArTPC technology appears scalable to fiducial mass scales of ≈ 100 kT, or more, that are likely required to address key questions, such as CP violation in the lepton sector. **FIXME:** *100 kton is NOT what we're designing!* Advisory committees such as NuSAG and P5 have strongly endorsed the development of LArTPC technol-

ogy as a significant step forward for both the neutrino and the wider particle physics communities. **FIXME:** *ref?*

In the overall analyzing power for long-baseline neutrino experiments, current estimates find an LArTPC to be equivalent to a WCD ≈ 6 times more massive. While neither an LArTPC nor a WCD requires great depth for accelerator neutrino detection because of **FIXME:** *'very effective'? need some adjective* background rejection achievable with a short spill **FIXME:** *clarify "short spill" unless EVERYBODY besides me knows it*, **FIXME:** *the inherent?* LArTPC background rejection also enables observational searches such as nucleon decay and supernova neutrinos at a moderate depth.

The specific, extraordinary aspects of LArTPC technology that enable detector optimization in the mass vs. background-rejection plane include:

- Highly accurate differentiation of electrons vs. photons by high-resolution measurements of electromagnetic shower development in the vicinity of the interaction vertex

- High-resolution reconstruction of the recoil hadronic shower, including nuclear debris, and

- Excellent sensitivity to low-energy hadrons, those that are below the Cherenkov threshold in water.

Although many technologies have been developed for particle detection, few have the combined properties of large active mass and high spatial and energy resolution that cryogenic, inert liquid detectors offer. Indeed, the only possibilities include emulsion detectors (extremely costly), bubble chambers (low duty cycle and complex mechanical systems) and liquid scintillator (LS). The NOvA Detector **FIXME:** *reference?*, with a mass of ≈ 15 kT, likely represents the limit of a feasible, segmented LS detector. An integrated-volume LS detector, viewed by high-resolution CCD devices, is a possible LBNE detector technology, but one that the collaboration is not pursuing at this time, because of the significantly better background rejection of the LAr technology. Indeed, no more information-rich strategy for neutrino experiments is visible on the technological horizon than LAr, except possibly the economical fabrication of silicon strip detectors with integrated electronics in multi-kiloton quantities, which is unlikely for at least a decade.

1.2.2   LAr20 Detector Overview

This Conceptual Design Report describes a particular LArTPC implementation, the LAr20 detector, as a next step **FIXME:** *next step? not 'a sound detector technology' or such?* towards achieving the scientific goals of the Long-Baseline Neutrino Experiment (LBNE). High-purity liquid argon **FIXME:** *mention temperature, e.g., "maintained under 87.3 K"* in LAr20's 16.7 kT fiducial mass serves as both the neutrino target and the tracking medium for the charged particles

1 produced in the interaction. The TPC active volume will be 15 m x 15 m x 34 m. **FIXME:** *does*
2 *this correspond to the fiducial mass?*

3   A uniform electric field in the LAr20 detector will cause the ionization electrons from
4 neutrino interactions to drift up to a distance of 1.5 m to three wire planes. **FIXME:** *need*
5 *illustration here* The electric potentials of the three wire planes will be arranged such that the
6 electrons pass through the first two "induction" planes, inducing bipolar signals on the wires
7 **FIXME:** *bipolar? Clarify.* , then get collected on the third, the "collection" plane, on whose wires
8 they will produce negative unipolar pulses. Cryogenic (submerged) electronics within the LAr20
9 vessel will amplify the signals on each wire and continuously digitize the amplified waveforms at
10 2 MHz. The proposed LAr20 wire pitch in all planes is 3 mm, yielding millimeter-scale position
11 resolutions **FIXME:** *"a factor of X better than current resolutions" or whatever....* We will
12 reconstruct the trajectory of particles in the detector from the known wire positions, the arrival
13 times of electron signals on the wires, and the time at which the interaction took place in the
14 detector **FIXME:** *known how?*. The amplitude of the ionization electron signals indicates the
15 energy loss of the particles, and thus allows an estimate of their momentum and particle type.

16 ### 1.2.2.1   LAr20 Main Features

17   Figure **FIXME:** *xxx* shows the main features of the LAr20 Detector. LAr20 will have a
18 single cryogenic volume, divided into four Time Projection Modules (TPMs). The TPMs will be
19 bounded at each end by cathode planes (five planes to demarcate four modules). Each TPM
20 will have a centrally located set of Anode Plane Assemblies (APAs), for a total of four APAs
21 in the detector. Each plane of wires (cathode and anode) will contain 13 wire frames, each of
22 which is small enough to be assembled remotely and transported underground as an integral unit.
23 The cathode planes will be held at an electric potential of -125 kV to create an electrical field
24 of 500 V/cm between the cathode and anode planes. This field will produce an electron drift
25 velocity in the LAr of 1.6 mm/μs. Each APA will contain four planes of wires in a wrapped
26 configuration, as shown in Figure **FIXME:** *xxx*. The wire planes are labeled *grid plane*, *induction*
27 *plane 1*, *induction plane 2* and *collection plane*. The purpose of the grid plane is solely to improve
28 the effectiveness of induction plane 1; it will not be instrumented with readout electronics.

29   A field cage will surround each row of cathode planes and APAs to ensure uniform electron-
30 drift trajectories near the detector edges. The field cage will be constructed of lightweight **FIXME:**
31 *xxx* diameter stainless steel tubes separated by **FIXME:** *xxx* cm. A resistor chain between the
32 cathodes and anodes will establish the electric potential of each field cage tube **FIXME:** *clarify*
33 *'tube'*.

1.2.2.2   The Cryogenic Volume

The TPC, consisting of the aggregate of the four Time Projection Modules will be surrounded on each side by a ground plane. The ground planes will ensure that electric fields in the argon gas ullage (the gas volume above the liquid) remain below **FIXME:** *xxx* kV/cm and the electric fields in the LAr remain below 1 MV/cm. The bottom ground plane also serves as a convection and bubble diverter in the event that localized heat leaks exist in the insulation.

The Time Projection Modules will be housed together within a cryostat that will contain the LAr and insulate it from external heat. Conceptual design studies resulting in this report suggest that the optimal choice for cryostat design is a single "membrane cryostat." The most notable feature of a membrane cryostat is the use of a thin metallic liner to contain the liquid argon. Figure **FIXME:** *xxx* shows a cross-sectional view of the membrane cryostat. The metallic liner will be constructed of 0.7 mm thick stainless steel, corrugated in both directions to enable thermal expansion and contraction. The liner will be attached to insulation units constructed of marine plywood boxes **FIXME:** *do people know what marine plywood is?* filled with polyurethane foam. The hydrostatic load of the liquid argon will transfer through the liner and insulation to the walls of the cavern, resulting in a highly efficient use of the excavated cavern volume. A secondary liner **FIXME:** *inside or outside the first?* will provide an annular space for argon gas purges. A tertiary liner **FIXME:** *same question* will prevent ground water infiltration.

1.2.2.3   Cooling

The cryogenics system for cooling the LAr in the membrane cryostat will be located primarily on the surface. Insulated cryogenic piping will connect the surface refrigeration and purification plant with the underground cryostat and the small portion of the cryogenics system that must sit adjacent to the cryostat. The mechanical components of cryogenics systems typically require considerable maintenance. A surface location simplifies installation and maintenance and minimizes Oxygen Deficiency Hazard (ODH) because of the enhanced possibilities for air circulation and venting. The cryogenics will be fitted with LAr pumps located near the cryostat, so that it will be possible to empty the cryostat and return the LAr to the surface.

1.2.2.4   Electronics

The LAr20 detector will feature "cold" electronics. The analog section of integrated electronics, mounted directly on the Anode Plane Assembly and within the cryogenic volume will amplify, shape and digitize signals from each wire channel. The digital section of these same electronics will provide zero-suppression and multiplexing. Optical fibers will route multiplexed signals through cryogenic feedthroughs located at the top of the cryostat. A distributed local computer cluster **FIXME:** *how can it be local and distrib?* will provide triggering and event selection. We

will store data locally and also transport data sets to Fermilab and other collaborating institutions for archival storage and offline analysis.

We will configure the detector electronics to enable both continuous and triggered data acquisition. Either a beam spill signal from Fermilab or a signal from a photomultiplier-based scintillator light detection system will initiate a trigger. A beam-spill trigger will initiate data collection from the entire detector, whereas a photon-detector trigger will initiate read out of wires only in the vicinity of the scintillation light source. Signals from some of the physics processes of interest may be below threshold for the light detection system (e.g., relic supernovae). Continuous readout of the detector provides a methodology **FIXME:** *or just a method?* for studying such processes, given sufficient computing resources to store and analyze (offline) the large amount of data that this readout mode will generate.

1.2.2.5   LAr Purity

For electrons to drift over several meters, electro-negative contaminants in the liquid argon — primarily water vapor and oxygen — can exist only at very low levels **FIXME:** *Can we quantify?*. To remove contaminants we will recirculate liquid argon through molecular sieves and copper filters. Purity monitors at the filter outlets will monitor their effectiveness. Whenever the first set of filters is saturated, argon flow will be diverted to a second set, and the system will circulate a 95% argon 5% hydrogen gas mixture at an elevated temperature through the saturated filters to regenerate them. A condenser will reliquify the argon gas boil-off from the top of the detector and purify it before returning it to the cryostat.

1.2.2.6   Depth Options

Selection of the depth for the LAr20 detector location represents a trade-off between less background and increased unit cost. For a fixed dollar budget, lower unit costs imply larger detector mass. As stated earlier, we seek a point in the mass-background plane (and thus a depth) that maximizes the physics potential of the LAr20 detector. The layout of the Homestake Mine suggests strong consideration of three possible depths:

- 300 feet. This shallow depth offers the advantage of approximately horizontal access via tunnels (to be constructed) from the canyon east of the Yates Shaft. However, cosmic ray background, from both the east and west sides, is likely to complicate non-neutrino beam measurements.

- $\approx$ 800 feet. At this moderate depth, both increased vertical overburden and a flatter (less mountain-like) depth profile reduces the cosmic ray background from that at the 300 foot level **FIXME:** *by how much?* . Adding an active shield to the LAr20 detector at this depth

would likely enable us to achieve competitive physics goals for a range of beam and non-beam experiments. Access to the LAr20 Detector Laboratory would be furnished through two dedicated, raise-bored shafts or declined tunnels, thus mostly isolating LAr20 from shaft contention with other DUSEL activities.

○ 4850 feet. This depth, at DUSEL's most active level, would significantly reduce the rate of background events and remove the need for an active shield. On the other hand, we would likely need to raise-bore one new, dedicated LAr20 shaft, and use the Yates and Ross shafts for secondary access. Further, this location would require more careful coordination with other DUSEL activities.

The conceptual design process has concluded that the most favorable depth for LAr20 is ≈ 800 feet. With the active shield, described later in this report **FIXME:** *ref*, LAr20 at this depth should be sensitive to most, if not all, of the possible physics range inherently afforded by this detector technology. Compared to the 4850 level, the preferred 800 foot level simplifies both access and the cryogenics system design, and reduces the possibility of shaft access contention with DUSEL and its other experiments.

1.2.3   Scientific Requirements

I imagine that the scientific requirements from the requirements document will be summarized or inserted here in it's entirety.

My playing around with a table.

Detector Parameters		
Parameter	Value	Motivation
Energy Resolution	<12% at 100 MeV	Neutrino oscillations

1.2.4   Civil Construction Requirements

The civil construction requirements for the LAr20 design are mostly conventional — a significant advantage. We plan to install LAr20 in a "rural mailbox-style" cavern, a rectangular solid with a slightly domed roof. Access and workspace will be located above the LAr level **FIXME:** *different than the surface?*, to provide secondary containment for the cryogenic liquid and also to use the cavern walls and floor to support the hydrostatic loads on the insulation surrounding the cryogenic volume **FIXME:** *how does this follow?*. We will install transverse **FIXME:** *steel?* beams, likely augmented by tensioned ties, to ceiling rock bolts, to support the insulated cover on top of the LAr. Mechanical, electrical, telecommunications and other support systems will likely be located either above the cryostat or in smaller caverns, adjacent to the top of the main detector cavern.

1   We expect the LAr20 cavern to be excavated by conventional means (drill, blast, muck).
2   We will stabilize the ceiling and walls by rock bolting as necessary, and line the ceiling with
3   shotcrete to prevent oxidation and exfoliation of the excavated rock. The walls will likely require
4   **FIXME:** *a layer of?* formed concrete to achieve a sufficiently smooth surface to support the
5   detector insulation. The floor will consist of poured concrete in direct contact with the excavated
6   rock.

7   The LAr20 laboratory **FIXME:** *define* will require two access shafts or tunnels, with suffi-
8   cient ventilation capacity to force one access downdraft and one updraft, even in the event of a
9   major cryogenic spill. **FIXME:** *means " force a downdraft in one access opening and a downdraft*
10 *in the other"?* We expect to use the downdraft shaft or tunnel for routine personnel access and
11 the updraft shaft or tunnel for equipment access. If tunnels are used, their lengths would be too
12 short for a Tunnel Boring Machine (TBM), so they will be excavated by conventional means.
13 Shafts would be raise-bored to minimize costs and increase safety.

14 ## 1.2.5   Primary Risks

15   We categorize the risks associated with the LAr20 detector as either technology risks or
16 project risks. The major risks associated with liquid argon TPCs have been highlighted in various
17 reports and presentations over the past several years.**FIXME:** *references?* While LAr20 will be the
18 largest liquid argon TPC ever to be constructed, much smaller LAr Detectors, such as ArgoNeut,
19 have worked well **FIXME:** *too vague.* The underlying design principles are already proven **FIXME:**
20 *ref*, the technology risks are primarily associated with scaling up by significant factors. With regard
21 to project risk, much can be learned from the considerable experience with Liquified Natural Gas
22 (LNG) at the 10^5 ton level. Outside engineering firms with considerable LNG experience have
23 contributed significantly to the development of this Conceptual Design Report. It is important to
24 note that of the primary risks we have identified, none is considered major.

25 ### 1.2.5.1   Technology Risks

26   The "Integrated Plan for LArTPC Neutrino Detectors in the U.S." (ref. bnl docdb #113)**FIXME:**
27 *Anne to add ref* has identified LAr technology risks using a bottoms-up approach. Some risks
28 originally designated as technology risks were re-categorized as project risks during the analysis.
29 The likelihood and consequence of each risk were classified using a semi-quantitative method
30 adopted from the NSLS II project. The study concludes that the R&D activities (ArgoNeut,
31 LAPD and MicroBooNE) mitigate LAr20 technology risks to an acceptable level. The study also
32 identified project risks for a large LAr TPC and recommended new R&D activities that the LAr20
33 project now addresses. This plan was reviewed by the Fermilab Directorate and submitted to the
34 DOE in December 2009. A brief summary of the technology risks and the current state of R&D
35 follows.

LAr purity vis-a-vis acceptable electron lifetime

All LAr TPCs operated to-date were first cleaned of contaminants by evacuating residual gases from the cryostat. This procedure is difficult to implement for a large detector in a cost-effective way. **FIXME:** *and so we are not considering it?*

R&D performed on the Materials Test Stand at Fermilab has shown that water vapor, not oxygen, is the primary contaminant that limits electron lifetime **FIXME:** *(Ref)*. Porous materials such as signal cables are the primary source of water vapor in the detector. Results from the Liquid Argon Purity Demonstrator (LAPD), also at Fermilab, demonstrate that purging the detector with hot, dry argon gas prior to filling can effectively remove water **FIXME:** *(Ref when it is done!)*.

Another important finding from Materials Test Stand studies shows that maintaining the water source temperature below 200K halts outgassing of water vapor **FIXME:** *from what?*.

The LAr20 design has incorporated these findings in several ways. First, we have chosen to use cold electronics **FIXME:** *clarify how this helps* and to cool all regions inside the cryostat to a temperature below 200K. Secondly, we will multiplex cables to minimize the cable mass in the ullage.

The maximum electron drift time in the LAr20 detector is xx ms. **FIXME:** *fix xx and how/why is this time set?* Measurements on the Materials Test Stand (MTS) show that an electron lifetime of 10 ms is routinely achievable, even though in the MTS the top of the cryostat is at room temperature. In addition, in 2009, a 120 liter TPC at Padua measured an electron lifetime of 21 ms **FIXME:** *Factor of 2 higher – how is this convincing?*. The world's largest existing LAr Detector, ICARUS, detector is currently operating with a xx ms **FIXME:** *fix* electron lifetime. These data demonstrate that the risk of unacceptably short electron lifetime is low.

Maturity of LAr physics and analysis software tools

Historically, the lack of simulations and reconstruction software has prohibited conducting detailed physics analyses to support the performance claimed for LAr technology. The LArSOFT group, composed of collaborators from ArgoNeut, MicroBooNE and LAr20, has made significant progress towards improvement of LAr-related software tools.

The LArSOFT group has developed general purpose packages that are usable by any of these experiments without duplicating effort. The current state of the software development is adequate to demonstrate that the LAr20 conceptual design meets the scientific requirements of the experiment. **FIXME:** *will we show plots supporting this later on in the CDR? Let's reference them.* The reconstruction software is also sufficiently mature to support the proposed CD-4 goal **FIXME:** *of what?*. While LAr20 software development will be an ongoing process, at this time, the risks associated with LAr20 software appear negligible.

Magnitude of the Scaling Between MicroBooNE and LAr20

¹ Choosing an optimal strategy for scaling technology from a smaller magnitude to a larger
² one **FIXME:** *give order of magnitude difference* always presents a challenge. The strategy we
³ propose here and in the Integrated Plan risk analysis envisions two steps — one from the already
⁴ successful ArgoNEUT to MicroBooNE scale **FIXME:** *scale of what?* and a second one, a factor
⁵ in volume of ≈ 240, from MicroBooNE to LAr20.

⁶ We acknowledge room for some skepticism. Although ArgoNEUT has produced stunning
⁷ event displays and its physics results are likely in the near future, published results are not yet
⁸ available. MicroBooNE will likely not publish physics results before ≈ 2014. The ICARUS Project
⁹ at the Gran Sasso (LNGS) has been underway for a considerable time and has yet to publish physics
¹⁰ results. Nonetheless, the risk analysis in the Integrated Plan concludes that the intermediate
¹¹ steps of ArgoNEUT and MicroBooNE are sufficient to inform the LAr20 detector design and
¹² implementation, and that the associated risk is not manageable **FIXME:** *NOT manageable?*
¹³ *Typo?* and not major.

1.2.5.2   Project Risks

Underground safety

¹⁶ The storage of a large inventory of cryogens underground poses a major Oxygen Deficiency
¹⁷ Hazard (ODH). The hazard is highest for occupants of the underground areas. A moderate hazard
¹⁸ to personnel above ground may exist in the event of a catastrophic failure of the detector cryostat if
¹⁹ the liquid argon is not vented properly. Risk depends on both the significance of the hazard and the
²⁰ probability of occurrence. Therefore, we mitigate the risk by reducing the probability of occurrence
²¹ of initiating events, and we plan to do so primarily by engineered controls. Administrative controls
²² are used sparingly. Ultimately then, the risk becomes one of poor design or implementation of
²³ these controls. We plan to minimize this risk by implementing a robust QA/QC program, described
²⁴ in Section xx.**FIXME:** *fix*

Association with DUSEL

²⁶ The Deep Underground Science and Engineering Laboratory (DUSEL) is a large and complex
²⁷ project. Multiple risks associated with the diverse suite of DUSEL experiments range from a safety
²⁸ incident involving any of the experiments to an overall management and funding risk associated
²⁹ with the DUSEL Project.

³⁰ The degree to which DUSEL risk affects LAr20 depends on the detector's location. An
³¹ LAr20 detector at the 300 ft or 800 ft level is only loosely coupled to DUSEL and its associated
³² risks, whereas at the 4850 foot level, the coupling is much tighter. Indeed, for an LAr20 Detector
³³ at either of the shallower levels, a substantial physical and managerial separation between DUSEL
³⁴ and LAr20 is possible, should factors arise that would motivate such a strategy.

1   Cryogenic Electronics

FIXME: *Is the basic idea that cold electronics are inaccessible, thus unfixable in case they break?*

The primary technical risk of cryogenic electronics is an unacceptably high level of coherent noise when a large number of channels are operated simultaneously in the detector. We will mitigate this risk first by careful design and a vertical-slice test of the electronics readout, and further by the use of optical fiber readout. Because coherent noise effects are independent of the cryostat temperature, we can make a full checkout of all electronics channels before filling the detector with liquid argon.

Another risk involves the inability to access the cold electronics once the detector is filled. The LAr20 detector relies on the constant and consistent operation over a period of about 20 years of more than 500,000 low-noise electronics channels in a sealed cryostat. The electronics design relies on the use of Application Specific Integrated Circuits (ASICs) to perform many of the functions usually performed heretofore by accessible **FIXME:** *and reparable? I think there are two issues you're referring to – you can't get at them, and if you could, you still couldn't fix them, right?* electronics modules. A study of cryogenic electronics operation in previous experiments has shown that the failure rates are negligible compared to standard room temperature electronics, most likely a result of the highly stable operating conditions. Electronics failures during low-temperature commissioning are essentially eliminated by robust qualifications**FIXME:** *quality?* testing of components at low temperature.

The combination of these procedures, in addition to the conclusion stated above that the use of cryogenic electronics mitigates the risk of poor argon purity, reduce the cryogenic electronics risk to an acceptable level.

2 Cryogenics System And Cryostat

The cryogenic systems associated with the liquid argon cryostat include:

L.Ar offloading and receipt facilities

o Transfer system to deliver L.Ar to the cryostat

o Boil off gas reliquefaction equipment

o Liquid argon circulation equipment associated with the purification plant

o L.Ar discharge/drain facilities

o Cryostat insulation purge facilities

o Temporary systems for cool-down

2.0.5.3 Cryostat Options

The required cryogenic systems and the associated design have not been found to be dependent on the form of the cryostat. The same systems are required whether the cryostat is of the membrane or modular design. Minor differences are anticipated with respect to penetrations through the roof structure, internal supports and arrangement of equipment within the caverns by virtue of the minor differences in the cavern layouts.

The cryogenic systems are similar for a shallow (300âĂŹ) cavern and the deep (4,850âĂŹ) cavern although the layout of the equipment is different. The cryogenic systems associated with a deep cavern require pressure control systems in the lines between the surface and the cavern due to the potential static fluid head.

2.0.5.4 Layout

The layout and location of the cryogenic systems has aimed to:

1   ○ Minimize the exposure of personnel to any Oxygen Deficiency Hazard (ODH) which may
2   occur due to working in close proximity to argon in a confined space

3   ○ Minimize heat ingress to the cryogenic transfer lines (by minimizing their length)

4   ○ Minimize the volume of the argon system external to the cryostat to minimize the potential
5   for argon escape, argon contamination and the overall argon inventory.

6   ○ Provide safe access for 3rd parties providing maintenance services to special equipment (eg
7   rotating plant)

8   The cryogenic systems will generally be located adjacent to the cryostat with services
9   provided from a small surface facility, as shown in figure 2.1. Risers and other pipework required
10 to link the cavern to the surface will be routed up the cavern ventilation shaft. The surface
11 facility will be located adjacent to the top of the shaft. The close proximity of the cavern to well
12 ventilated external areas has supported the location of the majority of the cryogenic plant and
13 equipment at the surface.

Fig. 2.1. Schematic Layout (placeholder)

14   The argon recondenser, the in-tank argon circulation pumps and the cryostat over pressure
15 protection systems are located in the cavern. All other equipment is located in the above ground
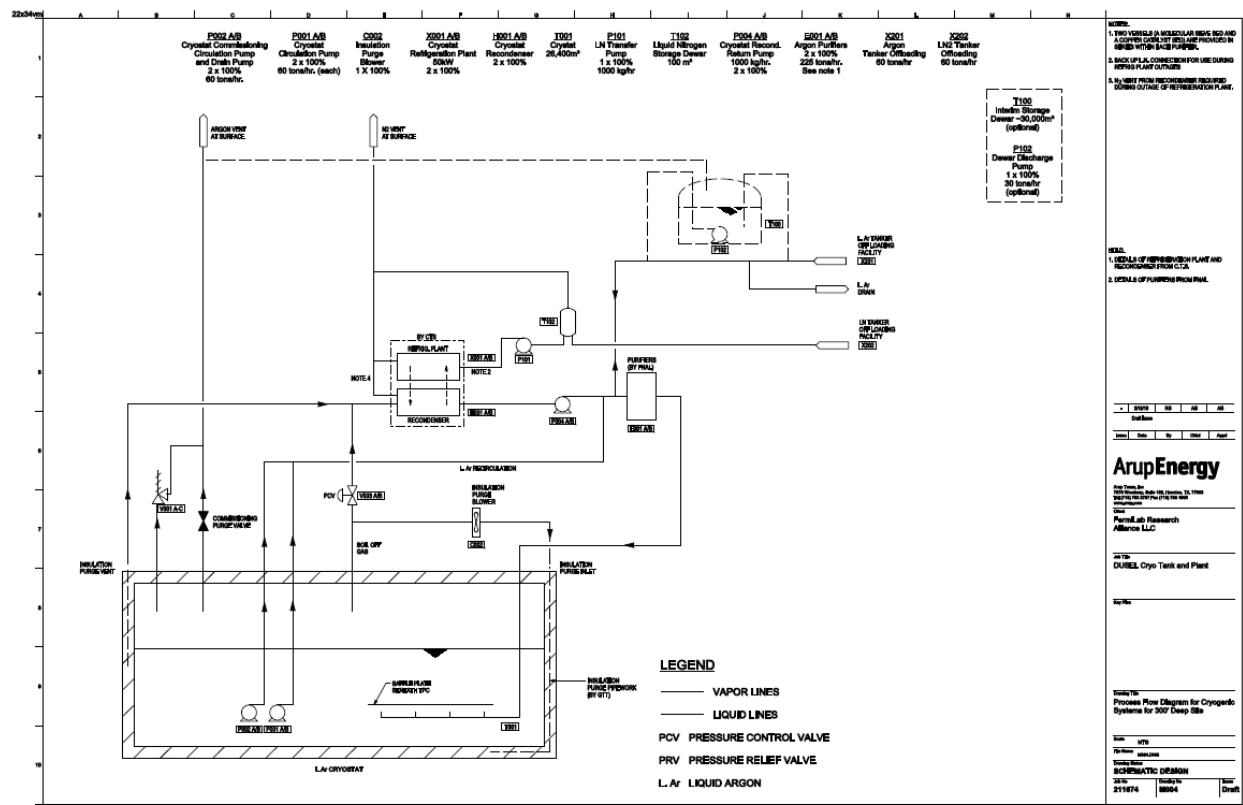
external compound. This arrangement facilitates construction, reduces the hazard associated with an argon leak and facilitates access for maintenance of key items of equipment. The arrangement extends the length of the circulation lines from the cryostat to the purifiers and of the lines between the argon recondenser and the refrigeration plant.

The following equipment will be located directly on or within the cryostat irrespective of the location or form of the cryostat.

- Circulation pumps to deliver L.Ar to purifiers

- Commissioning circulation pumps to deliver L.Ar to purifiers at elevated rate during initial purification period

- L.Ar return/fill line

- Boil off gas line

- Cryostat pressure control valves

- Cryostat pressure relief valves

- Purge pipework

- Cryostat monitoring equipment (pressure, temperature, density, depth etc)

All connections into the cryostat will be via nozzles or penetrations above the maximum liquid level and typically located on the roof of the cryostat. Equipment located within the cryostat such as monitoring instrumentation and pumps will be installed within wells extending through the roof structure.

2.0.5.5   Redundancy

Safety critical equipment has generally been provided on the basis of âĂŸn+1âĂŹ units. This will ensure that should a unit require maintenance or is not available for other reasons, then the cryostat operation will not be disrupted and safety will not be compromised.

Exceptions to this basis are typically items that are required for a short duration or where multiple units are provided. The former would have a low probability of failure and the latter assumes that failure of a single unit would not significantly impact the performance of the overall system.

Flexibility and resilience has been provided in a number of areas where a common specification has been developed for equipment on differing duties. Interconnection and or relocation

can then be used to mitigate failure of an item of equipment. An example of this would be the inclusion of separate argon and nitrogen delivery systems when simple piping crossovers and procedures could be adopted to permit one system to carry the alternative fluid in the event of equipment failure.

2.0.5.6   Maintenance

Facilities will be included for the safe inspection, maintenance and replacement of all cryogenic systems. Appropriate facilities would include closed vents and drains and purge pipework. Block valves and/or drop out spools will be provided such that appropriate positive isolations can be provided to support equipment maintenance while the cryostat continues to operate safely.

2.0.5.7   Cryostat Purge

On completion of the cryostat and following installation of all scientific equipment the cryostat will be cleaned, purged and cooled. Construction procedures will ensure that the completed cryostat does not contain debris and is free of all loose material that may contaminate the L.Ar.

The temperature of the cryostat will be gradually reduced, while ensuring a high level of Argon purity and eliminating any potential for moisture/ice formation. Measures will be taken during construction to minimize contamination levels and a high degree of cleanliness will be achieved.

The procedure for the membrane cryostat is as follows:

- Vacuum pump the cryogenics piping (not connected to cryostat)

- Purge the cryostat with several volumes of dry argon gas - vent to atmosphere

- Recirculate warm dry (50ÂřC) argon gas through the cryostat removing contaminants with filters. It is anticipated that this activity will be undertaken for several days

- Introduce high purity liquid argon to cool-down the cryostat. The rate at which L.Ar is introduced will be governed by the maximum cool-down rate that is acceptable for the cryostat components, outfitting elements and surrounding structure / ground. L.Ar that evaporates should be re-liquefied for all subsequent steps using the re-condenser and refrigeration plant.

- Recirculate L.Ar (at high rate) through the purification system

- When purity is achieved, reduce L.Ar recirculation rate to a level sufficient to maintain a uniform temperature distribution within the cryostat.

Internal piping within the cryostat will be required to support the purge and cool-down procedure. Heavy argon vapor will promote purging if it is delivered to the base of the cryostat and vented from the roof level. All venting will be contained and either vented outside of the cavern at a remote location or re- condensed using the refrigeration plant and re-used. Typical piping arrangements on LNG storage tanks that would also be appropriate for the cryostat include:

- Spray Header - The requirement for even cool-down of the cryostat and the high initial boil off rate may necessitate the use of a high level distribution ring main with multiple downward pointing nozzles.

- L.Ar fill pipework and reticulation to control the delivery flow regime and promote segregation / sweeping during the purge process

- Reticulation pipework within the insulation space to ensure complete purge (membrane cryostat only)

- Purge pipework to promote flow of purge gas within the perlite insulation (modular cryostat only)

- Multiple vent points to eliminate pockets under the roof where off spec vapor may collect

Liquid argon will be delivered to the cryostat through the cryostat filling pipework although it is anticipated that a number of small diameter lines will be required from the main fill line to distribute the L.Ar within the cryostat.. The flow through these lines will be manually controlled using suitable flow control valves. On completion of commissioning the cool-down and purge pipework will be isolated and removed.

2.0.5.8 Cryostat Filling

Liquid argon will be introduced into the cryostat through a roof level nozzle and pipework that will extend into the cryostat. The L.Ar supply line will be used to deliver the initial filling flow and the L.Ar recirculation return flow to the base of the cryostat. To minimize any local disturbance within the cryostat caused by the L.Ar in-flow it is proposed that a reticulation system will be provided beneath the TPCs with multiple outlets. A baffle plate below the TPC is to be employed. Gaseous bubbles may develop in the return flow line from the purifiers or from the âĂŸwarmerâĂŹ base and walls. The baffle plates will be positioned / designed to deflect the bubbles away from the fiducial volume.

LNG storage tanks are provided with two fill lines. One terminates at the base of the tank and one at high level. This arrangement allows the operator to select whether to place âĂŸnewâĂŹ LNG above or below âĂŸagedâĂŹ LNG. It is also possible to withdraw LNG from the base of

the tank and return it to the top of the tank. This allows the operator to manage the storage inventory so that stratification and the associated risk of âĂŸrolloverâĂŹ are prevented.

It has been assumed, for concept design, that

- drawing L.Ar for purification from the base of the cryostat,

- returning the purified L.Ar (at a similar elevation but at a remote location from the pumps) and,

- the boiling off of gas from the surface

will provide sufficient mixing to prevent stratification. If later analyses predict that stratification may occur then a high level fill line could be provided. If it is predicted that there is potential for stratification then inventory monitoring (temperature and density profiling) would be required. The pressure relief system would also need to be sized to accommodate any vapor release associated with a rollover.

The L.Ar inlet line will terminate below the normal liquid surface level so that turbulence, bubbles or splashing are minimized within the fiducial volume.

2.0.5.9   Argon Riser

A liquid argon riser is required between the cryostat in the cavern and the surface cryogen receipt facilities. The L.Ar riser will be used for the initial transfer of L.Ar to the cryostat during purging, cool-down and filling and to rain the cryostat (L.Ar from cavern to surface) operating with reverse flow.

The line will be fabricated from double walled vacuum jacketed pipe to achieve very low heat leakage rates. The line will not normally be in service and will therefore typically be at ambient temperature. Prior to any period of use the lines will be cooled.

2.0.5.10   Line Sizing

Line sizing is based on the maximum cryostat fill rate and the design requirement to limit liquid flow velocity to 2.5m/s.

The cryostat will be filled over a period of 90 days giving a flow rate of $12 m^3/$hr which will require a minimum pipe size of 75mm dia (3âĂİNB).

No consideration is necessary in this requirement for:

- o Purging: 10 complete volume changes would require 264,000mÂş of gas (1100mÂş of liquid)

- o Boil off gas associated with extracting heat from the cryostat and any surrounding structures (thermal heat capacity of the structure)

- o Boil off gas associated with the long term heat ingress over the cool-down period. The boil off gas will be recovered through the argon re-condenser.

2.0.5.11 L.Ar Transfer Pumps

A liquid argon transfer pump is required at the surface. This will be capable of delivering twice the flow rate at peak delivery than is required to fill the cryostat in 90 days. The additional capacity is to ensure that the average rate can be achieved even if L.Ar deliveries are disrupted and to minimize the standing time for tankers delivering L.Ar to the facility.

A low head pump is required to overcome the static head in horizontal sections of line at or near the surface. The L.Ar should generally transfer to the cryostat under gravity.

Pump Duty	Flow Rate (kg/hr)	Head Rise (m)	Hydraulic Power (kW)	Rated Power
L.Ar transfer from surface	35,000	10	900W	1.8kW

2.0.5.12 Deep Cavern Considerations

The vertical distance between a deep cavern (4,850âĂŹ) and the surface will necessitate the inclusion of pressure control stations within the L.Ar riser. The static liquid head pressure in a full argon line routed between the surface and the cryostat would be 202bar (2,930psi). A design pressure to accommodate this operating pressure would require heavy wall piping and high pressure pumps and fittings. This would result in a high capital cost for equipment which is utilized only for a short duration and an increased hazard in the event of leakage.

A piping system with a pressure rating in accordance with ASME B16.5 Class 300 would provide a design pressure up to 51bar (740psi). Pressure control stations would then be included in the risers to limit the static head to approximately 600psi. This would then allow a margin for friction losses in the system when fluid is being pumped from the cavern to the surface.

Six pressure reduction stations are proposed. Each pressure reduction station will include a vented break tank, level control valve and level controller fitted to the break tank.

The arrangement of the pressure control stations is shown on the Process Flow Diagram for the 4,850âĂŹ level cryostat. The vented break tanks should be sized to provide a 2 minute reaction time to the peak flow rate through the riser. This occurs during reverse flow when the

cryostat is being drained. They should therefore each have a capacity of $1.2m^3$ to provide ample time for control purposes.

The break tank vent will be connected into the cryostat over pressure protection system vent (discussed below) and released / recovered at the surface.

2.1 Requirements and Specifications

2.1.0.13 General Piping

Piping shall be metallic and designed in accordance with the requirements of ASME B31.3 Process Piping and ASME B31.5 Refrigeration Piping and Heat Transfer Components.

Pipe material shall be seamless Austenitic Stainless Steel in accordance with ASTM A312 Grade TP304 or TP304L. No corrosion allowance is required with this material in this service.

Cryogenic piping shall be laid to falls such that any boil off vapor is vented through the dedicated vent system or returns to the cryostat, interim storage dewar, or another vessel designed for vapor recovery.

Smaller bore vents and drains shall be provided as necessary to facilitate testing, commissioning and cool-down of the piping system.

A flange minimization policy shall be adopted for the L.Ar systems to reduce the risk of leakage. Flanges may be justified for the connection of the piping to proprietary equipment and vessels. The minimum flange rating shall be in accordance with ASME B16.5 class 150.

The design of the argon system shall aim to eliminate all fugitive ingress so as to ensure that the required levels of purity are maintained. In addition to the minimization of flanges discussed above, potential leak paths (such as valve stem packing) shall be eliminated where possible. Where leak paths cannot be eliminated a positive purge with gaseous argon shall be provided.

All piping systems shall be sized to limit liquid flow velocities to a maximum of 2.5m/s and gaseous flows to less than 20m/s.

2.1.0.14 Isolation

All pipe systems shall be designed such that pipe, plant and equipment may be isolated and removed from service for replacement or maintenance. All nozzles off the cryostat shall include isolation valves so that individual lines may be isolated from the gaseous inventory of the cryostat.

Where the pipe system design results in the potential for isolated sections of lines to be filled with cryogenic fluids (e.g. fluid trapped between valves) a means of relief shall be provided to prevent over pressure.

2.1.0.15   Insulation

All cryogenic lines, gaseous or liquid, shall be provided with insulation to minimize heat transfer to the fluid and to provide personnel protection.

Vacuum insulated pipe shall be used to minimize heat load and to simplify pipe support arrangements on straight runs. Internal bellow arrangements are preferred. Vacuum insulated pipe should be specified such that the outer pipe is pressure competent and will provide secondary containment in the event that the inner pipe fails.

Where necessary due to the number of connections, changes in direction or the inclusion of valves and fittings, mechanically insulated pipe may be used. All mechanical insulation shall be protected by waterproof cladding detailed to prevent water ingress.

2.1.0.16   Piping Support Arrangements

All piping systems shall be adequately supported to limit stress and vibration. Thermal, mechanical, environmental, installation, long term fatigue and seismic loads shall be considered.

Piping within the cryostat or within other vessels will be adequately supported or guided to minimize stresses and to accommodate differential thermal contraction as the vessels and piping cool.

Stress analysis shall be undertaken in accordance with the requirements of ASME B31.3.

2.1.0.17   Piping Routing

Cryogenic piping shall be:

- Routed to minimize the risk of impact damage from dropped objects or vehicles

- Routed to minimize incursions into walkways and access ways

- Provided with stepovers where access is required across pipe racks. Stepping on to pipe runs shall be prevented

1   Suction and return lines used for circulation of liquid Argon in the cryostat through the
2 external purifier units (during start-up and normal operating conditions) should ideally be located
3 at diagonally opposite corners in order to maximize the flow path. Flow disturbances often occur
4 within the vicinity of pipe ends which require that they be located away from the TPC. Ideally this
5 should be achieved without introducing large âĂIJdeadâĂİ spaces of liquid Argon at the cryostat
6 ends for example through the use of a localized rebate in the wall or in the TPC module.

7   One way to achieve this efficiently for the membrane tank is to locate a single pump tower
8 at the end of the tank (within the space required to complete the insulation/membrane following
9 installation of the TPC modules). The suction line is then located close to the pump tower while
10 the return line is routed down the pump tower and beneath the TPC modules towards the far end.
11 The TPC modules include shield plates (or baffles) across their base to prevent flow disturbances
12 caused by local heat variations which may occur at TPC support points. These baffles will act to
13 diffuse flow disturbances at the return pipe exit.

14   A similar arrangement is adopted for the modular tank. A 1.5 m extension of the cryostat in
15 the long axis provides sufficient clearance to locate the pump lines. This dimension also provides
16 adequate separation from the TPC units (to be confirmed by CFD analysis). Rather than provide
17 a separate tower, the internal structure is used to support the lines. The return line is similarly
18 routed beneath a shield plate located under the integral TPC.

19 ### 2.1.0.18   Pump Arrangement in the Cryostat

20   Pumps are required to transfer L.Ar from the cryostat as the vessel is designed without
21 penetrations below the normal liquid level. All of the pumps must be inserted and maintained
22 through roof top penetrations. Vertical submersible pumps that can be inserted into pump wells
23 extending down from the cryostat roof are therefore to be used. The length of the pump well
24 and the elevation of the pump is dependent on the function of the pump and any requirement to
25 draw L.Ar from the lower levels of the cryostat.

26   In similar LNG storage tanks the pumps are located as low as possible in the tanks to
27 minimise the heel (LNG remaining in the tank at the end of pumping) and therefore maximize
28 the net storage volume. The pumps are also used to âĂŸchurnâĂŹ the LNG within the storage
29 tank to reduce the potential for âĂŸrolloverâĂŹ that may occur due to stratification and LNG
30 ageing. The pump suction is normally located as low as possible within the tank and two return
31 / fill lines are provided that can deliver LNG to either the base or the upper levels of the tank as
32 determined by the Operator.

33   The cryostat requirements are different in that the L.Ar is not to be removed on a regular
34 basis (except for recirculating flow to the purifiers). The liquid level will therefore remain constant.

35   The circulation pumps have been specified on the basis that they will extract L.Ar from the

lower levels of the cryostat to permit their use during cryostat drainage. If dedicated drainage pumps are provided then the circulation pumps could be located at high level. This would result in a reduced head rise across the pumps, shorter cabling, shorter pump wells and a lower capital and operating cost.

The pump suctions must be located a minimum distance (normally 1.5 âĂŞ 2m) below the lowest liquid level at which they are to pump to prevent cavitation and vapour entrapment. The pumps and pump wells will therefore need to extend several meters into the cryostat.

Vertical submersible cryogenic pumps are supplied by manufacturers such as Ebara and Carter Cryogenic Products; see figure 2.2. A description of their cryogenic electro-submersible pumps is provided by Ebara below for information

2.1.0.19   Purification Turn-down Rate

To achieve the turn-down required between the short term commissioning flow rate (600gpm) and the long term operational flow rate (150gpm) through the purifiers a number of pump configurations are feasible.

Two pumps of 300gpm each could be provided that would operate as 2 x 50% during the initial commissioning phase. During the long term operation they would operate as 2 x 100% but would require further flow reduction. This reduced flow could be achieved by throttling the discharge flow, providing a bypass around the purifiers or by specifying the pumps with Variable Speed Drives (VSD). All of these reduced flow arrangements are inefficient and are not normally considered desirable for long term, continuous operations with steady flow rates.

An arrangement with multiple pumps could be provided. These pumps, say 4 No, would operate as 4 x 25% during the commissioning phase and 4 x 100% during the long term operation. This would provide a more flexible pump configuration. The progressive reduction in required flow rate as the L.Ar purification increases would be met by incrementally reducing the number of pumps operating. An appropriate number of pumps would be operated at anyone time to match the required flow rate with minor throttling occurring at the pump header if required. Individual pumps would therefore be able to operate more closely to their Best Efficiency Point, BEP (optimum flow rate). Long term the multiple pump arrangement would allow the pumps to be specified with their BEP closer to the desired long term continuous flow rate. Expensive VSDs are less appropriate in this arrangement due to the associated capital cost and the low utilization rate that would occur on individual VSD units (i.e. when only one pump is required). The multiple pump arrangement will provide a very high level of redundancy which will extend the cryostat operating period without maintenance.

A multiple pump arrangement has been selected. FNAL may wish to review this selection as their knowledge of the purification plant design develops. If the long term flow rate is not

This unique design allows the pump to be installed inside a storage tank in a vertical pump column, with a suction (foot) valve located at the bottom. Because the pump is installed through the top of the tank, all connections below the maximum liquid level of the tank can be eliminated. This eliminates the possibility of major tank leakage due to a pipe or connection problem. It also permits the storage vessel to be located below ground level or completely covered by mounding. The applicable codes allow the owner to minimize the land area needed to locate a liquefied gas storage tank due to the reduction of spillage potential.

The submerged pump and motor unit is designed to fit into the smallest practical column diameter by using an axial diffuser design. The column then acts as a guide to seat the pump during installation and also as the discharge pipe from the pump to the top of the tank. Each pump is fitted with an inducer, which is an axial flow impeller located at the lowest possible level of the tank to improve the NPSHR (Net Positive Suction Head Required) and allow operators to lower tank liquid levels to extremely low levels. To isolate the tank contents from the pump column, a suction valve is used, which incorporates a dual pressure sensitive seal. The valve is flanged to the lower end of the pump column and is closed by coil springs as well as by the hydrostatic pressure of the liquid in the tank.

The valve is opened by lowering the pump into the valve. The inlet feet of the pump press down against the bottom plate, forcing the valve to open using the weight of the pump. The valve can also be closed by simply lifting up on the lifting eye located at the top of the column headplate, without dis-assembly of any other components. Once the valve is closed, the column can be inerted with nitrogen gas to allow the safe removal of the pump even with liquid in the tank. The power cables used in the retraction system are a high quality armored cable, made especially for Cryodynamics. These cables are UL (Underwriter's Laboratory) listed, and were developed specifically for use in cryogenic liquids. The lifting cables used are an anti-twist, stainless steel cable, which can provide many years of use without replacement.

Fig. 2.2. Cryogenic submersible pump

anticipated to be constant or stable then the use of VSD drives and multiple pumps may be justified so that the delivered pump flow rate can closely track the flow demand. It has been assumed that the purifier plant will include the necessary inlet flow control valves.

Two pumps, each sized to deliver the long term circulation rate have been included in the design. This will ensure that during the early years of operation the recirculation rate could be

increased by 100% and in later years the two pumps can be operated in duty and standby mode so that a pump can be withdrawn from service for maintenance.

An arrangement with multiple pumps could be provided. Four pumps would operate as 4 x 25% during the commissioning phase and 4 x 100% during the long term operation. This would provide a more flexible pump configuration. The progressive reduction in required flow rate as the L.Ar purification increases would be met by incrementally reducing the number of pumps operating. An appropriate number of pumps would be operated at anyone time to match the required flow rate with minor throttling occurring at the pump header if required. Individual pumps would therefore be able to operate more closely to their Best Efficiency Point, BEP (optimum flow rate). Long term the multiple pump arrangement would allow the pumps to be specified with their BEP closer to the desired long term continuous flow rate. Expensive VSDs are less appropriate in this arrangement due to the associated capital cost and the low utilization rate that would occur on individual VSD units (i.e. when only one pump is required). The multiple pump arrangement will provide a very high level of redundancy which will extend the cryostat operating period without maintenance.

A multiple pump arrangement has been selected. If the long term flow rate is not anticipated to be constant or stable then the use of VSD drives and multiple pumps may be justified so that the delivered pump flowrate can closely track the flow demand. The purifier plant will include the necessary inlet flow control valve(s).

Two pumps, each sized to deliver the long term circulation rate have been included in the design. This will ensure that during the early years of operation the recirculation rate could be increased by 100% and in later years the two pumps can be operated in duty and standby mode so that a pump can be withdrawn from service for maintenance.

The increased commissioning purification flowrate is required for a relatively short duration. Two additional pumps capable of supplementing the normal circulation pumps will be employed to achieve the required flowrate. The normal circulation pumps and the supplementary commissioning pumps will be of similar specification and duty. Reliability over this short duration would be expected to be high but should a pump fail then the remaining pumps will be able to achieve the required flowrate (n+1 pump arrangement).

On completion of the initial purification phase the supplementary pumps can be decommissioned. They should not be removed from the cryostat as corrosion or other forms of deterioration are unlikely to occur and the pumps may be used in later life to provide additional redundancy or to supplement the normal pumps. The provision of multiple redundancies will extend that duration of cryostat operation ahead of any requirement to intervene to service or maintain the pumps. Intervention is undesirable as it will require men working in close proximity to the cryostat, the release and replacement of some argon and may result in the introduction of contaminants. This will result in an extended period of downtime while the purification specification is re-attained.

The pump data for the deep cryostat assumes that the refrigeration plant and purifiers are

located in close proximity to the cryostat within the deep cavern.

Pump Duty	Flow Rate (kg/hr)	Head Rise (m)	Hydraulic Power (kW)	Rated Power
Normal Circulation	2 x 60,000	30	2 x 5kW	2 x 15kW
Commissioning Circulation	4 x 60,000	30	4 x 5kW	4 x 15kW

Note that the head rise value is based on the hydraulic resistance of the purifier columns (2 x 55mbar), their close proximity to the cryostat and the elevation of the free surface within the cryostat. A 6âĂİ line is assumed.

The pump wells and foot valves are permanent installations and would remain within the cryostat during removal of a pump.

2.1.0.20   Pressure Control

The cryostat and associated cryogenic system form a totally closed system that prevents the ingress of air and other contaminants and retains the argon. To maintain the purity of the argon, the equipment within the system must exhibit a high level of integrity and leak paths should be eliminated.

During normal operation the heat ingress to the system will result in the liquid Argon boiling and expanding by a factor of approximately 240 (at atmospheric pressure) when it evaporates. This increase in volume within a closed system will, in the absence of a pressure control system, raise the internal pressure.

The rise in pressure may be controlled by passing the boil off gas to a re-condenser where it is cooled and condenses back to a liquid. It may then be returned to the cryostat. The reduction in volume within the re-condenser reduces the pressure at the inlet and draws further argon gas into the re-condenser (thermo siphoning effect).

The flow to the re-condenser is controlled by pressure control valves located in the boil off gas line (normally located on a cryostat roof nozzle). These valves should be specified to control the pressure between the preset maximum and minimum levels.

Normally the process control system will aim to maintain the gas cap within the cryostat at a pressure slightly above atmospheric pressure at all times to prevent air ingress. The pressure control valves are sized and set to control the pressure under normal operating conditions between two set points (50 and 200mbarg). Excursions above or below these levels will set off alarms to permit the operator to intervene. Further excursion may result in automatic (executive) actions occurring. These actions may include stopping the L.Ar circulation pumps (to reduce the heat ingress to the cryostat), increasing the argon flow rate through the re-condenser, increasing the LN flow through the re-condenser vessel, powering down heat sources within the cryostat (detector,

electronics) etc. Eventually if the pressure continues to rise the pressure relief valves will operate.

The ability of the control system to maintain a set pressure is dependent on the size of pressure upsets (due to flow changes, temperature changes, changes in atmospheric pressure etc) and the volume of gas in the system.

This cryostat is less prone to pressure upsets than cryogenic LNG storage as the stored volume of liquid does not change, there is unlikely to be any diurnal variation in the ambient temperature, and the cryostat will not be subjected to solar gain. Other special design cases that impact the pressure control system are applicable to flammable gas storage tanks, such as external fire, are not relevant to the cryostat.

It is desirable to minimize the gas cap so that the dimensions of the cryostat can be minimized while maintaining the fiducial volume. This will mean that volume changes will have an exaggerated affect on the pressure in the gas cap and on the pressure control system. The design of the re-condenser will also impact the controllability of the pressure. As the boil off gas cools and condenses the pressure in the re- condenser falls. Without inlet control this will result in a drop of pressure within the cryostat.

2.1.0.21   Pressure Control

Vent lines are required from the cryogenic systems to relieve over pressure and to assist with system purging. They will be required for both the argon system and the nitrogen system.

As argon is an asphyxiant and displaces oxygen even at low concentrations any argon vent line should be extended to a well ventilated remote area at the surface.

The argon cryostat overpressure protection vent line links the cryostat pressure reduction valves to the surface and provides a means of venting vapor from the argon pressure break vessels in the fill riser to the deep cavern.

The maximum flow that may need to be accommodated through the argon vent line is dependent on the heat ingress to the system. The anticipated heat ingress is 50kW however it would be prudent to design the cryostat protection system with some over capacity. The normal argon gas boil off rate is 1100kg/hr. The proposed design rate for the vent is 1500kg/hr (providing 35% over capacity). The overcapacity in the vent line will also ensure that the back pressure in the system due to dynamic losses is minimized. This flow is equivalent to a volumetric flow rate of 190m3 /hr (at 1.013bar and at the boiling point). A vent size of 150mm diameter (6âĂİNB) has been selected.

Nitrogen vent lines are also required and should be extended from the underground cryogenic systems to a well ventilated remote area at the surface. With the shallow cavern option nitrogen

will be vented from the re-condenser if the back-up LN supply is being used. The nitrogen vent for the deep cavern option will, in addition to the re-condenser flow, also accommodate flow from the refrigeration plant and the pressure break vessels in the fill riser.

The vent lines will be required during the initial cool-down and purge of the cryostat. The rate of gas evolution will be dependent on the procedure adopted. The lines have not been sized for this flow rate at this stage.

Cold argon and nitrogen vented from the cryogenic system will be significantly colder and denser than the ambient air in the cavern or at the surface.

NEED A VERSION OF TABLE 10 IN THE ARUP REPORT - PRESSURE HEAD AT VARIOUS DEPTHS

If the nitrogen vent flow rate is low enough and the vent lines are not insulated then as the nitrogen vents and warms it will rise and discharge because the specific density of nitrogen (as compared to air is less than 1 (0.967). The argon however has a specific density of 1.38 (>1.0) and therefore the vent lines will only discharge when the pressure at the base of the vent riser is sufficient to drive the heavy gas out of the vent at the surface.

The preference is to provide a mechanical extract system within the vent lines that will draw the cold vented gases to the surface.

2.1.0.22   Cryostat Overpressure Protection System

The cryostat over pressure protection system is a high integrity automatic failsafe system designed to prevent catastrophic structural failure of the cryostat due to excessive internal pressure. The overpressure protection system is in addition to the normal operational pressure control system.

The key active components are pressure relief valves (PRV) located on the roof of the cryostat. These monitor the differential pressure between the inside and the outside of the cryostat and open when the differential pressure exceeds a preset value.

The PRVâĂŹs are self contained devices and are not normally part of the control system. They are provided for tank protection and open rapidly at the set point. The valves are typically pilot operated whereby the pressure within a small bore sensing line is used to trigger a pilot valve that delivers the power fluid (compressed air) to the actuator of the PRV.

The installation of the pressure relief valves should be arranged such that each valve can periodically be isolated and tested for correct operation. The valves should be removable from service for maintenance or replacement without impacting the overall containment envelop of the

cryostat or the integrity of the pressure protection system. This normally requires the inclusion of isolation valves upstream and downstream of the pressure relief valves and at least one spare installed relief valve (n+1 provision).

A pressurized reservoir of power fluid should be provided to each valve to ensure that the valves will operate under all upset / shutdown scenarios.

When the valves open argon will be released and the pressure within the cryostat will fall. The valves are normally designed to close when the pressure returns below the preset level. The relief valves are arranged to discharge into the argon vent riser.

The argon vent riser from a deep cavern will be subject to static back pressure as described. The back pressure in the riser will increase under flowing conditions but this increase can be controlled by appropriate sizing of the line to ensure that the velocity of the gas in the line is kept low.

The design pressure of the cryostat is less than the back pressure in the riser from the deep cavern and will therefore prevent the relief system from protecting the cryostat. The mechanical ventilation plant within the vent system must therefore be considered to be part of the cryostat pressure protection system and specified accordingly. The plant should be specified with a high degree of reliability and redundancy. Duty and standby blowers (2 x 100%) have been included in the design.

To provide further protection a second set of PRVs with a set point slightly above that of the primary relief valves has been included in the design. The secondary relief valves would vent argon into the deep cavern. These relief valves would only open if the primary PRVs have failed to open or if the primary PRVs have opened and the mechanical riser ventilation plant has not operated. An assessment should be undertaken to determine the maximum rate of gas evolution (assuming that the normal vapor recovery system has failed) and the associated impact on the ODH. The relief arrangement has been reviewed as part of the provisional FMEA analysis described in section xxx.

2.1.0.23 Cryostat Overpressure Protection System

With LNG/LPG storage tanks vacuum relief valves are provided to protect the structure from low internal pressure, for example if the discharge pumps are operating with the inlet valves shut.

Theoretically gaseous argon condensing in the re-condenser could result in a reduced pressure in the cryostat (thermo-siphon) or a failure of the vent system when draining the cryostat could result in reduced internal pressure.

The vacuum relief pressure should be set to prevent inadvertent operation of the relief valves as this would allow air ingress to the cryostat.

The cryostat vacuum relief system is a high integrity automatic failsafe system designed to prevent catastrophic structural failure of the cryostat due to low internal pressure. The vacuum relief system should protect both the inner and outer tank. Activation of the vacuum relief system is a non-routine operation and is not anticipated to occur during the life of the cryostat.

The vacuum relief system is in addition to the normal pressure control system. The vacuum relief system is required to protect the cryostat during the initial purging operations when a controlled vacuum is to be created within the tank. The key active components are vacuum relief valves located on the roof of the cryostat. These monitor the differential pressure between the inside and the outside of the cryostat and open when the differential pressure exceeds a preset value. The relief valves will allow cavern air to enter the cryostat.

2.1.0.24   Cryostat Drain System - Maybe not needed

Section 4.6 text of Arup report not included here until we know if this is needed.

2.2   Liquid Argon Delivery and Storage (WBS 1.5.2.2)

2.2.1   Description

Facilities are required for the offloading of LN and L.Ar road tankers.

2.2.1.1   LN Delivery

LN offloading facilities will be provided adjacent to the storage vessels. Vehicle access and hard stands are required adjacent to the offloading facility.

2.2.1.2   L.Ar Procurement

XXX Describe the availability and procurement issues, including testing requirements at the supplier.

2.2.1.3 L.Ar Delivery

Requirements for the delivery of L.Ar are dependent on the cryostat purge, cool-down and the fill procedure and include the rate at which L.Ar is required, the ability to accommodate interruption of the supply and the quantity of L.Ar that may be vented prior to the commissioning of the refrigeration plant.

The logistics and supply of L.Ar to the facility include the following considerations:

- Total capacity of commercial air separation plants within freight distance of the facility (the peak delivery potential)

- The extent of boil off that will occur in transit

- The number of vehicle movements required

- The costs and benefits associated with stockpiling L.Ar at the facility ahead of commencing the purge, cool-down and fill procedure

- Provision of a temporary air separation plant at the facility to generate liquid argon

- The availability and cost associated with the delivery of high purity L.Ar as opposed to low quality commercial grade argon and providing on site coarse purification.

This current concept design has assumed that a sufficiently continuous and reliable supply of L.Ar can be arranged such that a stock piling facility (surface dewar) is not required. XXXX - NEED A DECISION HERE.

Road tankers will connect to a manifold located close to the access road portal and will use their on- board pumps to transfer the L.Ar to the cavern. If necessary, due to the capability of the on-board pumps, a static L.Ar transfer pump may be required at the portal. The connection of multiple tankers to the manifold will increase the flow rate and ensure continuity of supply at critical stages in the filling procedure.

XXX Include a description of acceptance testing.

2.3   Argon Reliquefaction (WBS 1.5.2.3)

2.3.1   Description

High purity liquid argon stored in the cryostat will continuously boil due to the heat ingress into the cryostat. The argon vapour (boil off gas) is to be recovered, chilled, recondensed and

returned to the cryostat. A closed argon system is required to prevent the loss of the high purity argon.

Gaseous argon will be directed to a heat exchanger (re-condenser) where it will be chilled against a stream of liquid nitrogen and condensed back to a liquid. As the gaseous argon cools the volume reduces and further gas is drawn into the heat exchanger developing a thermal siphon. A pressure control valve on the boil off gas line will control the flow to the re-condenser so that the pressure within the cryostat is maintained between preset limits. The liquid nitrogen stream will be a closed loop system. The system will include a refrigeration plant based on compression/expansion and heat rejection that will continuously cool the liquid nitrogen stream.

A duty and a standby refrigeration plant (2 x 100%) will be provided along with a duty and a standby re- condenser. This will ensure a high availability of the recondensing system and minimize any requirement to vent high purity argon. The arrangement will permit the re-condensers and the refrigeration plants to be maintained. The condensed stream of L.Ar will be combined with the L.Ar circulating stream and purified prior to being returned to the cryostat.

2.3.1.1   Equipment Layout

To minimize heat ingress to the re-condenser plant the re-condenser vessel, the refrigeration plant and the cryostat should be located in close proximity. However, the refrigeration plant includes rotating equipment (compressor and expanders) and as such is likely to require maintenance intervention and personnel monitoring.

The shallow cavern arrangement assumes that the re-condensers are located on the roof of the cryostat and that the refrigeration plants are located at the surface portal to the cavern access road. Heat ingress must be minimized in the lines between the refrigeration plants and the re-condensers. The deep cavern arrangement assumes that the re-condensers and the refrigeration plants are located within the cavern. The associated recondensing pipework will therefore be short.

A concept design for a modular skid mounted refrigeration system and re-condenser has been prepared by Cryogenic Technical Services (CTS). CTS are a division of Eden Cryogenics LLC. CTS are based in Longmont, Colorado. They provide consulting and design services and undertake custom fabrication of process equipment. Their proposal is included in Appendix xxx. The proposal excluded the re- condenser but subsequently details of this item have been provided and are presented next.

2.3.1.2   re-condenser

CTS have proposed a conventional cryogenic boiler/condenser for the argon cryostat. In this configuration the cold high pressure nitrogen is throttled into the top of the low pressure

boiling nitrogen reservoir which surrounds a large number of relatively short vertical tubes that are closed at the top end. Argon vapor is drawn up inside these tubes and is condensed. The condensed argon runs down the inside diameter of the condenser tubes and is collected to run back into the argon cryostat. Generated cold nitrogen vapor flows out the top of the assembly and returns to the liquefier through a vacuum jacketed line.

The condenser assembly will sit on top of the argon cryostat and communicate with it through a large diameter, short vacuum jacketed pipe, as shown in 2.3.

Liquid argon will return to the cryostat through a smaller tube inside the large pipe or will be drawn off and combined with the purification circulation flow and returned to the cryostat via the purifier plant. The vacuum jacket of the argon re-condenser will be approximately 1100mm (42âĂİ) in diameter and its total height should not exceed 1250mm (48âĂİ). The nitrogen reservoir will have a capacitance liquid level gauge with an indicator/controller. The controller will limit the liquid level in the reservoir and resulting pressure increase will cause the compressor to partially unload to reduce flow. This is the principal control for the whole liquid nitrogen refrigeration system.

It is estimated that the argon vapour line from the cryostat will be a minimum of 150mm dia (6âĂİNB) and that the condensate return line will be at least 50mm dia (2âĂİNB). As the re-condenser will be close coupled to the cryostat the vapour line will be of minimal length.

2.3.1.3   Recondensed Argon Return Pump

A pump will be required to direct the recondensed L.Ar to the purification plant. The recondensed flow will be combined with the circulation flow from the cryostat.

If it is found that the recondensed argon is of sufficient purity to be returned to the cryostat without passing through the purification system then it may be possible to delete the return pump and use a co axial return line as shown above in section 4.7.2.as the L.Ar will flow into the cryostat under gravity.

The recondensed argon return pump will be a low pressure centrifugal pump located adjacent to or within the re-condenser skid. It will be specified to transfer the anticipated volume of recondensed liquid and will require a nominal head rise to overcome pipework resistance and back pressure within the purifiers.

Pump Duty	Flow Rate (kg/hr)	Head Rise (m)	Hydraulic Power (kW)	Rated Power (kW)
Re-condensed Argon	1120	10	0.03	0.06
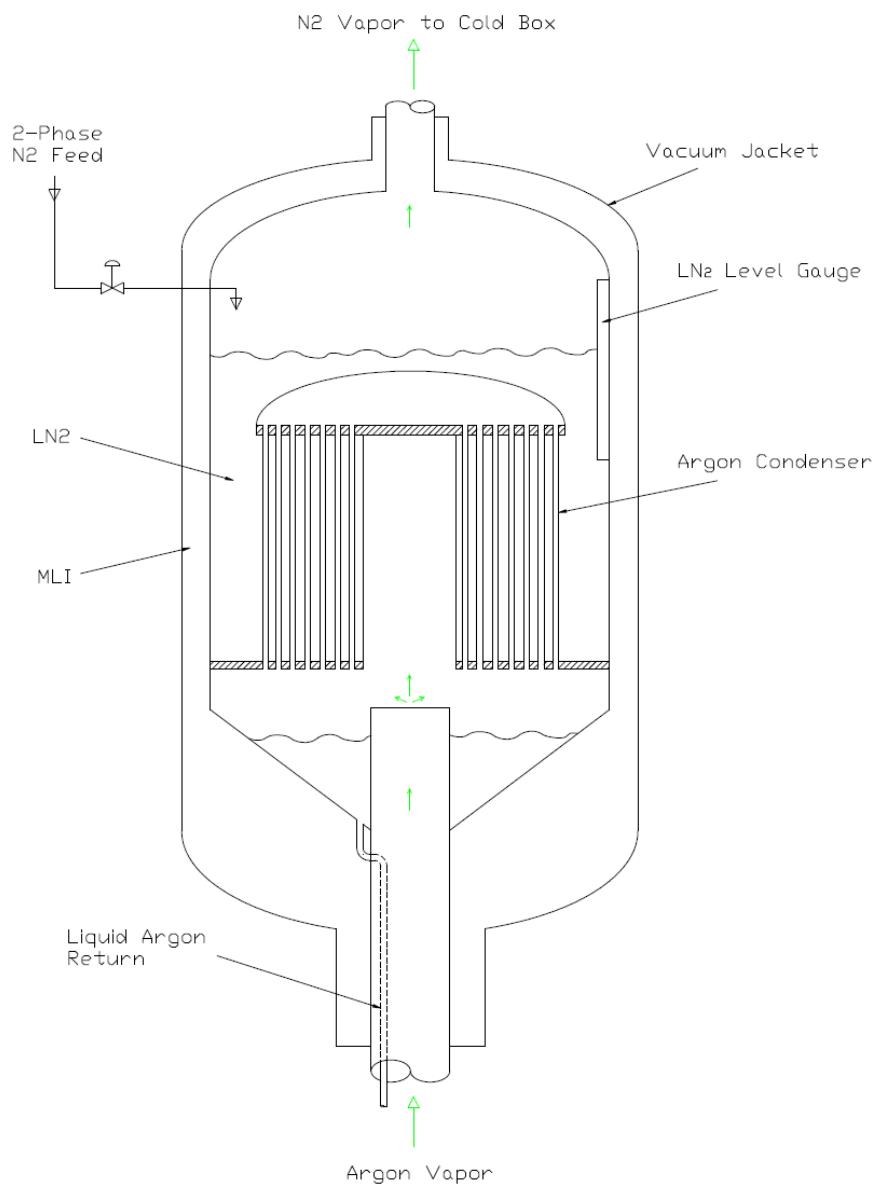
Fig. 2.3. Argon re-condenser

₁ **2.3.1.4   Insulation Purge System**

₂   A continuous purge of gaseous argon will be applied to the insulation space around the
₃ cryostat to prevent infiltration of water vapor and oxygen in the event of a microscopic leak.

₄   A side stream from the boil off gas line has been provided and it is assumed that approx-
₅ imately 10% of the boil off gas will be used to purge the insulation. This will result in a flow

rate of $20m^3$ /hr. The free volume within the insulation that is available for the accumulation of argon liquid or other impurities will depend on:

- The size of the individual insulation panels,

- The shrinkage that occurs during cool down (that results in gaps between the panels

- The total volume of insulation (cryostat surface area x thickness)

- Any open pores within the insulation

- Any volumes (corners etc) not fully filled with insulation

- Volume of the purge piping.

It has been conservatively estimated that the insulation voids should not exceed $60m^3$. The purge rate will therefore result in approximately one volume change every 3 hours.

The current cryogenic system design assumes that the purge gas that is discharged from the insulation space will be co-mingled with the boil off gas stream prior to being re-condensed, purified and returned as L.Ar to the cryostat.

A blower is provided to drive the purge gas through the insulation voids. A spare is not provided since the purge system is not safety critical and therefore an outage of the blower would have minimal short term impact on operations.

2.4   Liquid Argon Purification (WBS 1.5.2.4)

2.4.1   Description

The liquid argon within the cryostat must achieve and be maintained at a very high purity level.

Commercial grade argon will be delivered to the cavern and will pass through the purification plant before entering the cryostat. The argon will then be circulated for a period of time through the purification plant until the desired purity specification is consistently achieved. Purification will continue, albeit at a reduced L.Ar flow rate, to maintain the attained purity during the subsequent experiment / testing phase.

The purification plant will consist of a duty stream and an identical standby stream each consisting of a molecular sieve column and a copper catalyst column.

Redundant equipment will:

- allow regeneration of one system while the other is operating

- allow both units to operate in parallel during the initial cryostat filling period where a high throughput is required

- provide a maintenance contingency

Key design parameters associated with the physical arrangement of the purifier columns include a molecular sieve bed column of size 2m diameter x 6 m tall and a catalyst bed column of size 2m diameter x 6m tall. The pressure drop through each bed is 55kPa(8 psi) for a total of 110kPa.

The purifiers will be located close to the cryostat to minimize the volume of L.Ar in the circulation pipework and the pump power required to achieve the desired flowrate. Locating the purifiers at the surface is unlikely to be viable due to the extended L.Ar flowlines, the associated heat gain and the pump power requirements. Additional excavation is required to accommodate the columns in the cavern.

The specified initial circulation rate of 600gpm corresponds to an exchange of the gross L.Ar volume (26,400 m3) in 8.1 days; the long term exchange would take 32.3 days. The heat load introduced to the cryostat for the initial circulation rate will result in a significant increase in the total heat ingress beyond the long term 50kW refrigeration capacity. Additional refrigeration is required during the commissioning phase. However the refrigeration plant and re-condenser have been provided on a fully redundant basis to ensure high availability. During the initial period the plants will be operated in parallel to provide the increased cooling capcity that will be required.

2.5   Cryo Instrumentation and Monitoring (WBS 1.5.2.5)

2.5.1   Description

A dedicated control and monitoring system is required.

This will be a high integrity system providing remote monitoring and control of key functions from a control room located at the surface or off-site.

Remote control functionality will include:

- Cryostat pressure control

- ○ Control of the flow rate to the purifiers

- ○ Purifier control

- ○ Refrigeration system control

- ○ Unplanned switch over from duty to standby plant

Local (manual) control will be provided to:

- ○ Start and stop L.Ar and LN transfer pumps

- ○ Adjust the cryostat purge rate

- ○ Effect equipment isolation, purge and vent for maintenance

- ○ Planned switch over from duty to standby plant

Monitoring will be provided of key process parameters and of plant condition (pump vibration etc). Flow, pressure and temperature will be measured at strategic locations on the plant to provide operational data and to provide early warning of upset conditions.

A cascaded alarm system will be provided giving multiple levels of warning and alarm ahead of executive action. In addition to the control and monitoring system a separate emergency shutdown system shall be provided. This system shall be based on failsafe systems and shall be designed primarily to facilitate the safe evacuation of personnel from the facility. The emergency shutdown system shall inhibit in tank pump operation and close key isolation valves. The cryostat pressure relief system shall be considered to be part of the emergency shutdown system. A data historian shall be provided to record control commands, responses and measurements. The control system shall be configured to permit off-site monitoring and control via telemetry links.

2.6   LN2 System (WBS 1.5.2.6)

2.6.1   Description

A schematic of the refrigeration plant design and a description of the associated compressors and expanders are included with the CTS proposal. CTS propose to provide a closed loop nitrogen system to supply approximately 50,000 W of refrigeration to the liquid argon re-condenser. Two-phase nitrogen is delivered at 84 K to the re-condenser to allow a 5 K temperature difference against the 89 K argon re- condenser temperature.

The refrigeration system is based on the use of a centrifugal compressor and three turbo expanders for a clean, oil-free loop. This should ensure high reliability. It is expected that this system will run continuously for at least a year and then require only minor servicing. The system will be equipped with automatic controls and a remote panel so that no operator will be required during normal operation. Estimated maximum power requirement is 750 hp (560 kW) without credit for power generated by the expanders.

The refrigeration plant will have a heat output of 140kW.

A cold box will be supplied as part of each refrigeration plant consisting of four heat exchangers. These exchangers provide staged heat transfer from a cooling nitrogen stream to a warming nitrogen stream. The expanders are used to progressively reduce the pressure of the cooling nitrogen stream. Compression is carried out at close to ambient temperature. A compressor aftercooler is provided that will reject heat.

The refrigeration plant will be located on the surface. See figure 2.4.

The preliminary physical dimensions of the refrigeration plant is presented in the CTS proposal. They have also advised that the compressor skid will weigh approximately 3630kg and that the cold box will weigh 5670kg.

2.6.1.1 LN Storage Facility

A three day supply of LN as a back up inventory is considered to be reasonable and this would require a storage volume of approximately $100m^3$ (80 tons) based on a heat load of 50kW. During this three day period it is assumed that either the refrigeration plant would be repaired or the liquid nitrogen storage vessels could be refilled.

Liquid nitrogen storage vessels of this size would typically be vertical or horizontal cylindrical vessels constructed with a double wall and vacuum insulated. Heat ingress to these vessels will result in some boil off and opportunities for common ownership / use across the DUSEL facility will be explored. The LN storage vessel(s) will be located at the surface in an area accessible for road tanker deliveries.

2.6.1.2 LN Supply Pump

A liquid nitrogen delivery pump will be required to charge the refrigeration plant and to deliver liquid nitrogen to the re-condenser in the event that the refrigeration plants are not available. The pump should be sized to deliver the equivalent of 50kW of cooling as the nitrogen evaporates (20 tons/day).
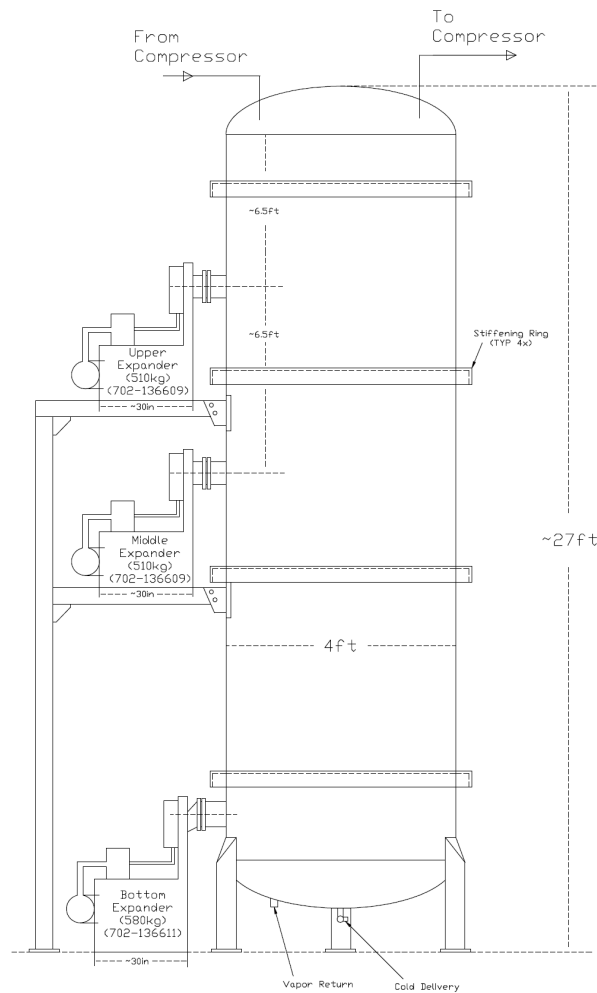
Fig. 2.4. Nitrogen refrigeration plant

1   The pump will not have a spare as the initial charge of the refrigeration plant and any
2   subsequent topping up will be a planned procedure. The requirement to use the pump as a back
3   up for the refrigeration plants is a secondary level contingency and a spare is not justified in these
4   circumstances.

Pump Duty	Flow Rate (kg/hr)	Head Rise (m)	Hydraulic Power (kW)	Rated Power (kW)
LN Supply Pump	910	10	0.03	0.06

6   Line sizing is based on the maximum LN demand whilst minimizing the pressure drop in
7   the line. A 50mm dia (2âĂİNB) line is considered to be adequate.

8   The re-condenser is located in the cavern but the refrigeration plant is located on the
9   surface. It is therefore necessary to transfer liquid nitrogen from the cool end of the refrigeration
10 plants approximately xxx m to the re-condenser. This transfer line (figure 2.5) will extract some

1 cooling power from the liquefier due to the pressure drop and heat leak. A preliminary concept
2 for this line is to send the high pressure liquid (a vapor/liquid separator would be installed at the
3 delivery end of the liquefier.) through an inner line surrounded by two concentric pipes forming an
4 annular flow passage. Multilayer insulation would be applied to the outer annular tube with a final
5 vacuum jacket pipe enclosing the assembly. A sketch of this design concept is included below.
6 Preliminary calculations indicate that the xxx m transfer line is feasible if the line is carefully
7 designed and fabricated to achieve low heat leak.

8   The transfer line is designed to deliver the product xxx m each way with a pressure drop of
9 less than 1 psi.
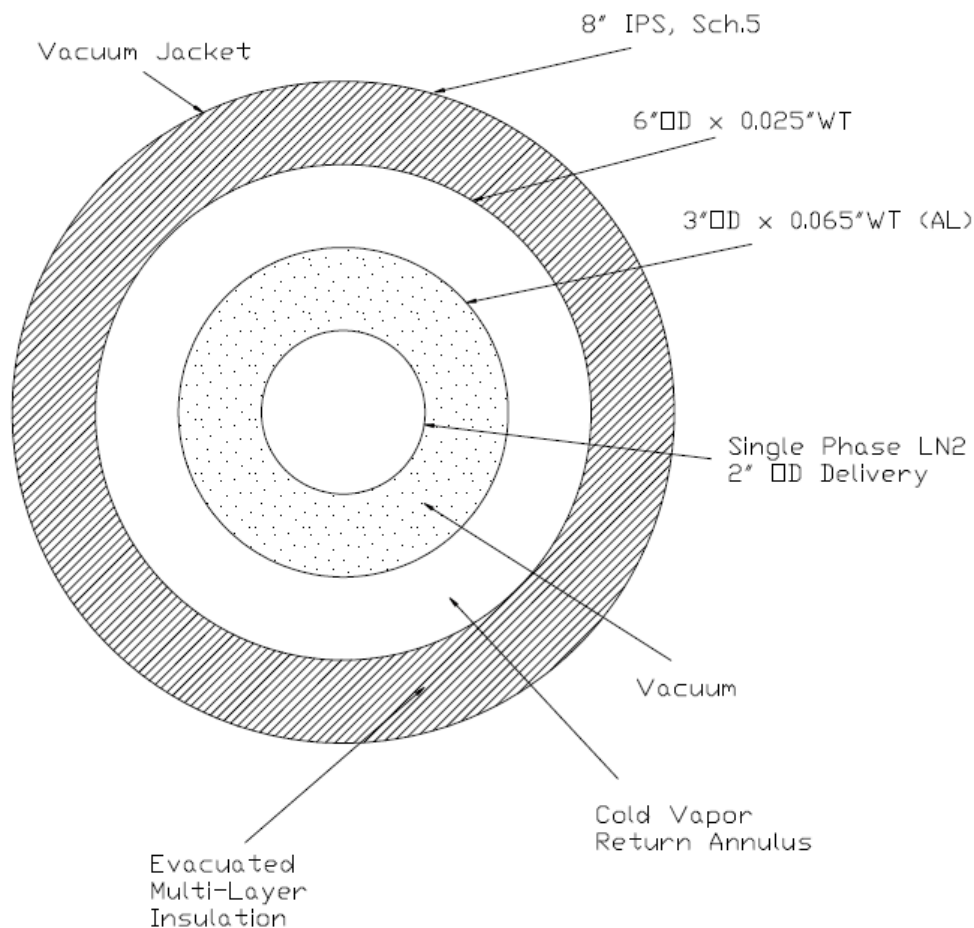
Fig. 2.5. Long distance transfer line

2.7   Cryogenics System Checkout (WBS 1.5.2.7)

2.7.1   Description

Blah blah on Cryogenics System Checkout Description.

2.8   Options Considered

2.8.0.1   Boil Off Gas Options

Alternative arrangements with regard to handling the argon boil off gas that have been considered include venting the boil off gas and replacing the lost volume with fresh L.Ar and re-condensing the boil off gas using an open LN system A coarse whole life cost estimate was prepared to compare the two optional schemes with the selected closed loop LN refrigeration plant.

2.8.0.2   Argon Venting

Venting the argon gas that boils off from the cryostat was considered as the minimum equipment and minimum capital cost option. Argon would be released from the cryostat to a well ventilated, remote area above ground. A make-up stream of L.Ar would be provided to maintain the gross volume within the cryostat.

Concerns raised by this system were:

- Ability to achieve required cryostat purity with a continuous stream of commercial grade argon entering the cryostat

- Reliability and availability of liquid argon supplies in the vicinity of Lead, SD.

- Continuing cost of supplying L.Ar throughout the life of the cryostat.

2.8.0.3   Argon Re-condensing by LN boil off

To recover the boil off gas emitted from the cryostat it is necessary to extract heat from the gas so that it cools and recondenses. The L.Ar can then be returned to the cryostat.

Cooling using an open liquid nitrogen system was considered. This system included a recondenser supplied with liquid nitrogen. Within the recondenser the boiling LN (at -196°C extracts heat from the warmer argon stream (at -186°C) and evaporates. The nitrogen is then vented. In cooling the argon gas it condenses and can be drained from the vessel.

A proposal was obtained for a suitable recondenser which has provided the details illustrated in figure 2.6:
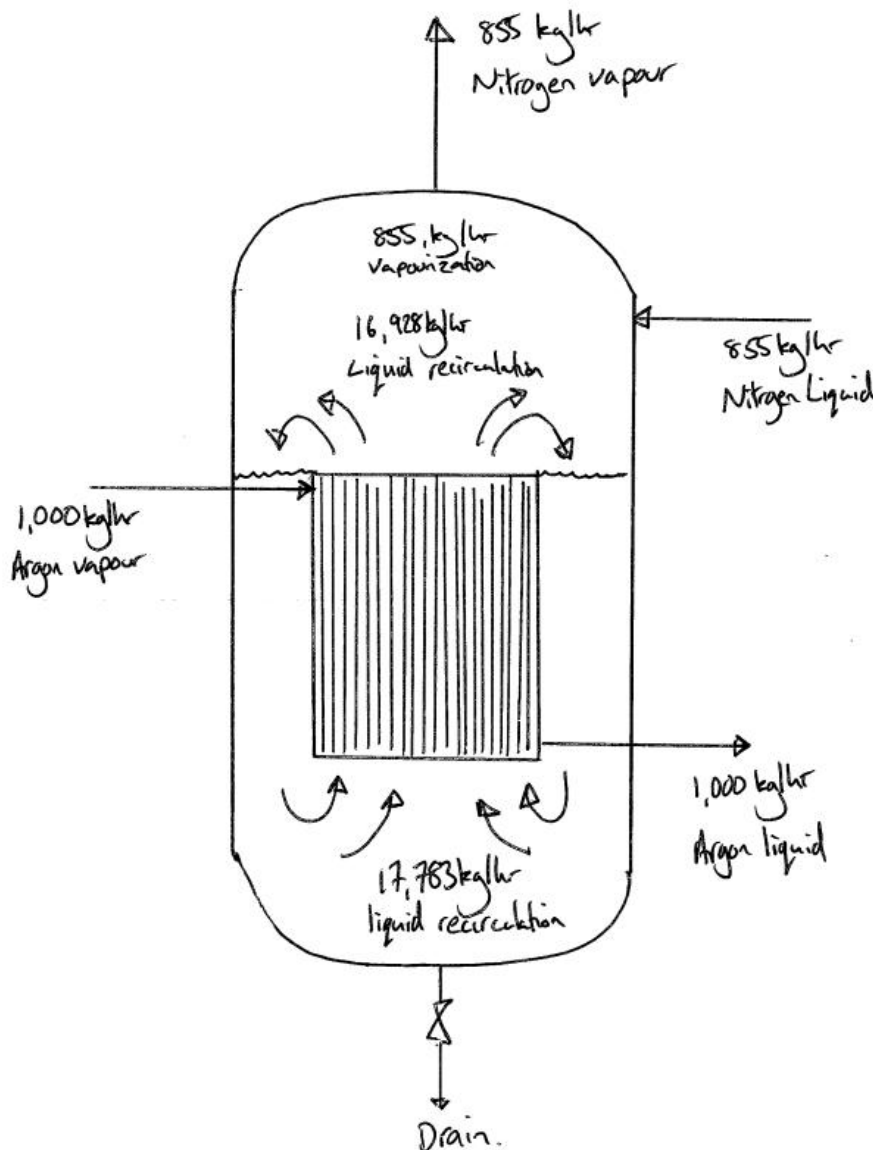
Fig. 2.6. Alternative argon re-condenser

A number of potential suppliers of bulk LN were also contacted. Cost estimates were requested for the supply of 20tons of LN per day and a stock holding on site of 80tons. A wide variation in price was received as the supply of LN is highly dependent on the cost of transportation

to the site from commercial air separation facilities.

Storage tank costs were typically quoted as a rental rate. Most large users contract for a long term supply of LN and the supplier provide and maintain the necessary facilities at the customer's plant. This includes monitoring inventory levels, determining restock schedules, undertaking deliveries and undertaking all necessary inspections and maintenance of on-site equipment. The lowest costs were provided by Praxair supplying LN from their air separation plant in Loveland, Colorado.

A whole life cost comparison estimate was undertaken of the two options and the selected arrangement with a closed loop nitrogen refrigeration plant. The analysis is included below:

Option	Estimated Capital Cost	Annual Operating Cost	Total Discounted Opera
Argon boil off and replace	$1.6M	$9.5M	$92.4M
LN open loop	$1.2M	$2.1M	$20.8M
LN refrigerated cycle	$4.0M	$0.6M	$5.5M

Notes:

1. The Estimated Capital Cost" includes engineering, equipment cost and installation in current fiscal year dollars.

2. The "Annual Operating Cost" includes utilities and maintenance (3% of capex).

3. The "Total Discounted Operating Cost" was calculated using a 20 year operation at a 5% annual discount rate.

The analysis was undertaken during the concept engineering phase of the study and therefore the costs should be considered as indicative only. However the analysis clearly demonstrate a significant cost benefit from selecting the refrigeration plant based recovery system. The higher capital cost is offset by operational savings over the 20 year design life.

However as a back up to the refrigerated closed loop nitrogen system a LN supply has been provided. This assumes that a relatively small supply of LN would be maintained on-site and would only be used when the refrigeration plant was unavailable. The on going cost of this provision is low due to the low cost of LN, the smaller inventory on site and the ability to control boil off by adopting vacuum insulated storage tanks.

2.8.0.4   Optional L.Ar Surface Dewar

The outline project requirements provided included a L.Ar storage facility to be located above ground. This surface dewar was to be capable of storing the full liquid inventory of the

underground cryostat. The proposed dewar would be an above ground or in ground cylindrical insulated tank with an available storage volume in excess of 26,400m3. It would be constructed as a double wall, perlite insulated storage tank. The dewar would:

- o provide interim storage for consolidating delivered L.Ar prior to cryostat fill,

- o offer emergency storage of L.Ar,

- o provide buffer for Argon boil off vented from cryostat in upset condition (although, concerns were raised over surface refrigeration capacity for this condition),

- o and could be used as a buffer for multiple cryostats (for the future condition).

An associated refrigeration plant would be required to recovery the gas which would boil off from the stored liquid. The dewar would be maintained at cryogenic temperature for the life of the cryostat so that should a cryostat leak occur then the dewar would be immediately available. This would require a long term inventory of L.Ar and continuous operation of the refrigeration plant. It is estimated that a $30,000 m^3$ dewar with 50kW of refrigeration plant would be required.

The dewar would be filled by the pumps located on the delivery tankers or the offloading facility pumps. An electro-submersible in-tank pump would be required to transfer fluid from the dewar to the cavern.

There will therefore be a capital cost and an operational cost associated with provision of the dewar.

The capital cost of the dewar, associated transfer pumps, circulation pumps and refrigeration plant has been estimated as follows.

Item	Cost
Dewar structure	$15M
Pumps	$2M
Minimum argon inventory	$3M
Refrigeration Plant (50kW)	$3M
Capital Cost	**$24M**

The operating cost of the storage dewar has been estimated as follows:

Item	Cost
Refrigeration plant power (200kW)	$190k
Maintenance (2% of capital cost)	$400k
Annual Opex	$590k
Net present cost	**$7.7M**

The cost of providing and maintaining the surface storage facility should be compared to the benefits that may accrue.

The Net Present Cost of providing the dewar is estimated to be $32M.

In terms of the value of the argon that may be recovered from the cryostat in the event that a significant leak occurs the benefit is less than $26.4million per incident.

The current cost of the dewar exceeds the current cost of replacing a single inventory of L.Ar.

This cost comparison ignores:

o the low probability of a significant leak developing due to the design of the cryostat containment system,

o the quality controls that are applied during construction,

o the testing that can be undertaken after construction, and

o the diminishing cost (in current terms) of the replacement argon.

It has not been possible to fully evaluate the benefit that may accrue during the cryostat filling procedure from the presence of the surface dewar. The dewar provides the capability to stockpile L.Ar at the facility prior to filling the cryostat. This will only be of benefit if the dewar filling procedure is significantly less onerous that the cryostat filling procedure.

2.8.0.5   Tanker Delivery of L.Ar to the 300 level - **DONT THINK WE NEED THIS**

2.8.0.6   Combined L.Ar and LN risers

The potential for the replacement of the two liquid cryogen risers (L.Ar and LN) with a common cryogenic riser should be considered during later design phases. The lines are not normally used during operation. After initial filling of the cryostat the argon line is not planned to be used unless the cryostat is to be drained. The common line would be configured in standby mode for LN service in case of unplanned outage of the refrigeration plant.

2.8.0.7   Common Vent Lines

A common vent system could be adopted that would be suitable for both nitrogen and argon. It would need to be sized for the peak combined flow rate. The probability of either argon

or nitrogen being vented under normal operations is low but a Simultaneous Operations Study (SIMOPS) would be required to demonstrate that cross contamination could not occur during commissioning, normal or emergency operations. A greater level of design detail is required to support this study than has been possible to date and therefore separate vents have been included at this stage

2.8.0.8   Alternative Nitrogen Cool-down Procedure

As an alternative to cooling the cryostat with liquid Argon a more cost effective procedure may be to cool the cryostat with liquid nitrogen and purge the cold cryostat with argon.

The procedure would be as follows:

- Purge with warm dry nitrogen (gas) to remove moisture

- Cool with liquid nitrogen

- Evacuate N2 using vacuum pump

- Purge with pure cold gaseous argon

- Repeatedly evacuate and replace argon to achieve purity close to L.Ar supply purity

- Fill with L.Ar

- Circulate L.Ar through purification plant to achieve purity required

The availability of large quantities of liquid nitrogen is substantially better than that of liquid argon and the cost is far lower. The viability of this procedure has not been proven.

2.8.0.9   L.Ar Supply using Temporary Air Separation Plant

We have considered whether the provision of a temporary dedicated air separation plant could be justified based on the elimination of L.Ar losses due to boil off during transportation, elimination of vehicle movements and the potential increase in the supply reliability. These advantages must be offset against the net capital cost of the temporary plant, the operating cost of the plant and the relative inefficiency of the âĂŸsmallâĂŹ temporary plant as compared to a large commercial plant.

3 Time Projection Chamber

The Time Projection Chamber is located inside the cryostat vessel, completely submerged in liquid argon at 87K. This subsystem includes all mechanical components of the TPC: anode plane assemblies, cathode modules and the field cage. It also includes all in-vessel electronics, signal and power cables, their feedthroughs, as well as the low and high voltage power supplies feeding the electronics. This subsystem interfaces the cryostat subsystem through the TPC mounting fixtures.

The TPC's active volume (fig.3.1) is 14 m vertically and 15 m horizontally and 70 m long in the beam direction. It contains ∼20 ktons of liquid argon. It consists of 4 columns of cathode modules, interleaved with 3 columns of anode plane assemblies. The distance between the cathode and anode is 2.5m. Both the cathode and anode plane assembly are 2.5m wide and 7m high. In each column, there are two rows of 28 modules. The total number of anode plane assemblies is 168, cathode modules is 224. Each pair of cathode and anode columns are surrounded by a field cage to ensure a uniform drift field.

On each anode wire assembly, 3 planes of wires cover both sides of a wire frame. The 3 planes of wires are oriented vertical, and ±45° respectively. At a wire pitch of 3mm, the total number of wires per assembly is about 4000, resulting in a 672,000 readout channels in the whole detector.

The readout electronics are optimized for operation in the cryogenic environment. The front end ASIC chip is a mixed signal design. It has 16 channels of preamp, shaper and ADC in its analog section, followed by input buffer, compression logic, output buffer for each channel in the digital section, and a 16 to 1 multiplexer at its output. 8 of such chips are mounted on a single readout board, covering 128 wires. An 8:1 multiplexer on this board further increases the multiplexing factor to 128:1, resulting in a single output channel. This single output channel is connected to both a LVDS driver and a laser driver to generate redundant outputs on both copper wires and optical fiber. On each wire module, there are 32 LVDS output channels and 32 optical fibers. Further multiplexing (8:1) on the optical channels with redundant output at the module level is being considered. The total output signal connections per module with 4000 wires is 64 copper wires and 8 fibers.
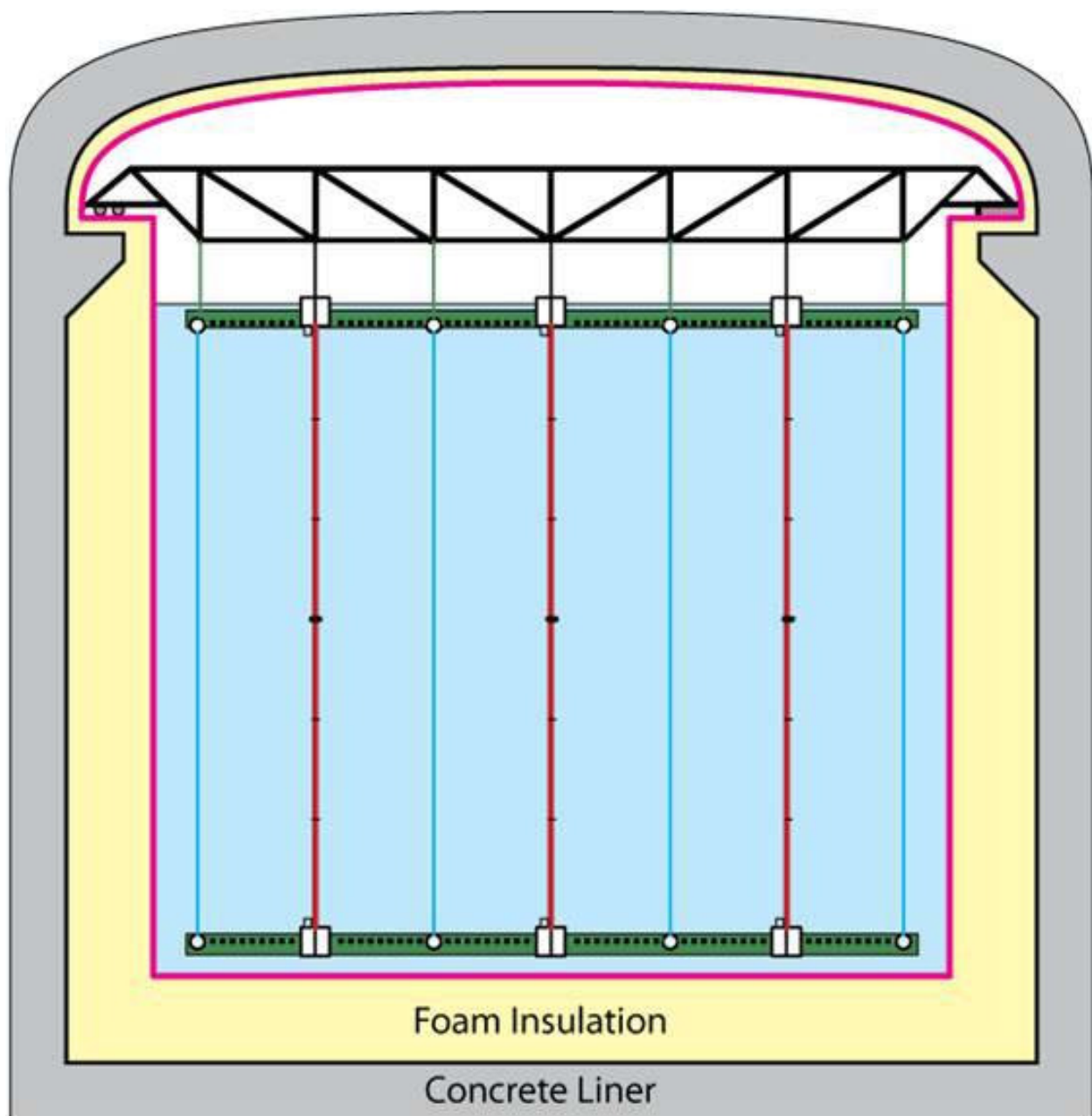
Fig. 3.1. Cross section of the TPC inside the cryostat (place holder)

To get the signals out of the cryostat, we need feedthroughs for a total of about 11,000 copper wires and up to 1500 fibers. Additional redundant high voltage (for the cathode), medium voltage (wire bias, optical readout), and low voltage power feedthoughs are also needed.

3.1   Requirements and Specifications

The main requirements of the TPC are the followings:

- The fiducial volume enclosed by the TPC must reach 100kton water equivalent.

- The TPC must be constructed from modules to minimize installation time and cost. Every module must be validated through thermal cycling to ensure compatibility with the LAr environment.

- 3 wires planes must be instrumented to provide redundant signal readout.

- The wire pitch should be between 3 − 5mm. The wire plane seperation should be equal to that of the wire pitch.

- The maximum wire length is 10m, to minimize the readout electronic noise.

- The wire chambers must be designed constructed to minimize the risk of wire breakage.

- The TPC must maintain a uniform electric field of 500V/cm, resulting in an electron drift velocity of 1.6 mm/μs. The field cage must keep the field uniform within 5cm of the field cage surface.

- The electric field must be kept below 100kV/cm in liquid argon, xxkV/cm in gas argon, throughout the cryostat to prevent high voltage breakdown.

- The readout electronics must provide a minimum signal to noise ratio of 10 for MIPs.

- The readout electronics must be designed to record the wire waveforms continuously without deadtime.

- The readout electronics must provide redundant multiplexed data output to minimize the number of feedthrough penetrations.

- All materials used in the TPC must be tested and qualified to be compatible with high purity liquid argon.

3.2   TPC Chamber (WBS 1.5.4.2)

3.2.1   Requirements and Specifications

Another pile of repeated text.

3.2.2   Description

3.2.2.1   Anode Plane Assemblies

The anode plane assemblies are 2.5m wide, 7m high, and about 7cm thick. Each is constructed from a framework of light weight stainless steel tubes, with 3 layers of CuBe wires wrapped over both sides of the frame.

3.2.2.1.1   Wire choices

3.2.2.1.2   Wire frames

3.2.2.1.3   Wire boards

3.2.2.1.4   Winding machines

3.2.2.1.5   Readout boards and their enclosures

3.2.2.1.6   Assembly and testing procedures

3.2.2.2   Cathode Modules

Similar to the wire modules, the cathode modules are also 2.5m wide and 7m high. Each is made of a stainless steel framework, with a layer of stainless steel wire mesh stretched over the entire opening. To reduce distortion to the drift field, all raised surfaces (SS frame) in the active volume will be covered with field shaping strips biased at appropriate voltages.

3.2.2.3   Field Cages

Each pair of facing cathode and wire module columns form a drift volume. To maintain a uniform drift field, a field cage is constructed around its 4 outer open edges. The field cages are made of sheets of copper clad FR-4 boards. Parallel copper strips on the FR-4 boards are interconnected by a resistive divider network. These strips provide a linear voltage gradient, ensuring a uniform drift field in the TPC's active volume.

3.3   In-Vessel Electronics (WBS 1.5.4.3)

3.3.1   Requirements and Specifications

- The in-vessel electronics must be designed to operate at a liquid argon temperature of 87K with a lifetime of 30 years.

- The front end electronics must have an ENC of $<1000e$ with an input capacitance of 200 pF, the equivalent of 10m wire.

- The total power consumption of all in-vessel electronics should not exceed 1/3 of the total cryostat heat load through the foam insulation.

- The front end electronics must digitize the wire signal waveform at no less than 1 MHz and 11bits of resolution.

- The readout electronics must operate either in a triggered mode or a continuous mode with no dead time loss.

- The front end electronics must provide sufficient level of multiplexing to reduce the number of feedthroughs, and redundant output to ensure reliability.

- The in-vessel electronics must be able to reliably transmit the digital signal through cables/fibers inside the cryostat to feedthroughs at least 50m away.

3.3.2   Description

The readout electronics are optimized for operation in the cryogenic environment. The front end ASIC chip is a mixed signal design. It has 16 channels of preamp, shaper and ADC in its analog section, followed by input buffer, compression logic, output buffer for each channel in the digital section, and a 16 to 1 multiplexer at its output. 8 of such chips are mounted on a single readout board, covering 128 wires. An 8:1 multiplexer on this board further increases the multiplexing factor to 128:1, resulting in a single output channel. This single output channel is

connected to both a LVDS driver and a laser driver to generate redundant outputs on both copper wires and optical fiber. On each wire module, there are 32 LVDS output channels and 32 optical fibers. Further multiplexing (8:1) on the optical channels with redundant output at the module level is being considered. A schematic diagram of this layout is shown in fig.3.2. The total output signal connections per module with 4000 wires is 64 copper wires and 8 fibers.

3.3.2.1   Front End ASIC

3.3.2.2   Data Transmission and Drivers

3.3.2.3   Readout Board

3.4   Feed Throughs (WBS 1.5.4.4)

3.4.1   Requirements and Specifications

- High voltage feedthroughs must be able to withstand -250kV at their center conductors and in 1 atm air or argon gas environment.

- Medium voltage feedthroughs must be able to withstand $\pm$1kV with leakage current less than xx nA in 1 atm argon gas.

- Low voltage power feedthroughs must be able to deliver a total of xxxx A of current

3.4.2   Description

There are 5 types of feedthroughs in the cryostat: High voltage feedthroughs provide -125kV to the cathode planes; medium voltage feedthroughs deliver bias voltages to the different wire planes; power feedthroughs carries the large current needed for the cold-electronics; LVDS and optical fiber feedthroughs transmit bidirectional electrical and optical signals.

3.4.2.1   High voltage feedthoughs

The cathode planes are biased at -125kV to provide the required $500\,\mathrm{V/cm}$ drift field. Multiple power supplies and feedthroughs are needed to provide redundancy.

The argon purity monitors will require a few lower voltage ($\sim$10 kV) feedthroughs.

3.4.2.2   Medium voltage feedthoughs

Each anode plane assembly requires two bias voltage connections at $+400$V and -200V. The current on each of these voltages is expected to be under 20 mA. However the ripple voltage on the supply must not exceed xx μV to avoid noise injection into the front end electronics.

3.4.2.3   Low voltage power feedthoughs

Even if we use in-vessel DC-DC converters, the current required to power all the cold electronics is in the order of kilo-amperes.

3.4.2.4   LVDS signal feedthoughs

The number of conductors on the LVDS feedthroughs is expected to be about 11,000. A small number of connections will be used for the temperature sensors and purity monitor outputs.

3.4.2.5   Optical fiber feedthoughs

The number of optical fibers in the cryostat is expected to be about 1500. A few special feedthroughs may be needed to transmit high intensity UV light to the argon purity monitors.

3.5   TPC Cabling (WBS 1.5.4.5)

3.5.1   Requirements and Specifications

Blah blah on TPC Cabling Requirements and Specifications.

3.5.2   Description

3.5.2.1   High voltage distribution

3.5.2.2   Bias voltage distribution

3.5.2.3   Low voltage power distribution

3.5.2.4   LVDS signal connections

3.5.2.5   Optical fiber connections

3.6   Power Distribution

3.6.1   Requirements and Specifications

All power supplies must be able to be monitored and controlled both locally and remotely through the DAQ system. They must have over-current protection circuits.

The 670,000+ channels of in-vessel electronics in the cryostat consume up to 10kW of power. Their DC power supplies must be capable of providing the needed current through the power feedthroughs into the cryostat. The ripple voltage on the output must be less then XXmV at full load.

The cathode planes are biased at −125kV. The cathode panels are connected into XX groups, each powered by its own HV power supply. The total current from the resistive dividers of a group is expected to be XXmA. The power supplies must be capable of providing this current with a voltage ripple less than XXmV. They must be programmabled to trip (shutdown) their output at certain current limit. During power on and off, including output loss (for any reason), the voltage at the feedthrough must be controlled to not exceed xxV/s to prevent damage to the in-vessel electronics through charge injection.

The U and Y wire planes are biased with voltages ranging from -300V to +600V. Power supplies for these wires must provide up to xxmA of current with less than xxmV of voltage ripple.

3.6.2   Description

3.6.2.1   High voltage power supplies

The current candidate for the high voltage power supplies is the Heinzinger PNC*hp* series.

3.6.2.2   Medium voltage power supplies

3.6.2.3   Low voltage power supplies

To provide more than 10kW of power at 2.5V would require 4,000A of current through and distributed throughout the cryostat.

3.6.2.4   In-Vessel low voltage DC-DC converters

High current feedthroughs require conductors with large cross sections. These conductors in turn become sources of heat loss. To reduce the heat loss, DC-DC step down converters are used throughout the cryostat. Since these converters consumes some power, they should be mounted in the gas volume above the TPC to prevent excess bubbling of argon.

3.7   TPC Instrumentation and Monitoring (WBS 1.5.4.6)

The TPC Instrumentation and Monitoring system consists of a distributed array of temperature sensors, argon purity monitors and liquid level monitors. Information obtained through these sensors guide the operation of the cryogenic plant, and provide calibration data for the TPC.

3.7.1   Requirements and Specifications

- The temperature sensors must have an accuracy of 0.1K at 90K.

- The liquid argon level must be measured with an accuracy of $\sim$1 cm. An interlocking system must ensure the cathode bias voltage be enabled only when the liquid level is above a threshold.

3.7.2   Description

3.7.2.1   Liquid argon purity monitors

Multiple purity monitors are located inside the cryostat in order to monitor the electron lifetimes. Oxygen and water monitors sample both liquid and the gas above the liquid.

3.7.2.2   Temperature sensors

Several temperature monitors located at various depths in the argon measure the temperature of the argon as well as any gradients that may develop.

3.7.2.3   Temperature sensors

Liquid level monitors are installed near the liquid gas interface to record the level of the liquid argon. The cathode high voltage power supplies must be interlocked with the level monitors in order to shut down the high voltage when the liquid level drops below a threshold to prevent high voltage discharges in the argon gas.

3.8   Interfacing to Other Subsystems

3.8.1   Requirements and Specifications

3.8.2   Description

3.8.2.1   Grounding and Shielding

Being an underground installation at a dedicated location, the most likely sources of EM interference are the cryogenic plant. Coordination between the cryogenic/cryostat and the TPC subsystem throughout the design, construction and installation phases is crucial to minimize electronics noise in the TPC signal.

3.8.2.2   TPC attachment

How will the TPC modules be attached to the cryostat? Hanging the entire TPC from the cryostat ceiling is preferred for minimizing structural materials inside the active volume, but

requires a more complex cryostat ceiling structure.

3.8.2.3   TPC readout and control

The data format and control protocols will be developed with the DAQ team.

3.8.2.4   Storage, Transportation, and Installation

Storage, transportation and installation of the TPC components will be described in the installation section (Ch. 7) of this CDR.

4 Trigger and Data Acquisition

The trigger and data acquisition subsystem (TDAQ) for the LBNE Liquid Argon TPC will serve the functions of (1) controlling operation and data read out of the detector,(2) receiving raw data from the front-end electronics system and from ancillary hardware, (3) filtering that data and constructing event records to be logged to persistent storage media, (4) monitoring detector and environmental conditions as well as data quality/integrity, and (5) performing online calibrations of the detector as required. The TDAQ will comprise a combination of custom and commerical hardware and firmware, commodity computing hardware, and both commercial and internally developed software.

The scale of the main task of handling digitized data from the TPC is determined by physics considerations, both directly and indirectly through their influence on the design of the TPC and front-end electronics systems. As described in Chapter 3, achieving sensitivity to signals that occur independently of the LBNE beam spill, such as those from nucleon decay or supernova neutrino bursts, requires a free-running transmission of data from the full detector at a $2MHz$ sampling rate. Data transfer is enabled by multiplexing and data compression in front-end ASICs in the liquid, and fast optical links that provide connection to data acquisition hardware outside the cryostat. Event building and triggering/filtering will thus be accomplished outside the cryostat.

Details of system design will depend on several key factors yet to be determined: for example, on detector depth (and hence atmospheric muon rate), and on the implementation of a trigger signal based on detection of prompt argon scintillation photons. For the reference design described in this document, we assume a detector location at the 800-ft level of the Homestake mine, and we assume no photon signal. Implications of alternative detector configurations for the TDAQ will be discussed briefly.

This chapter is organized as follows. In Section 4.1, we summarize the requirements that must be met by the TDAQ. Where appropriate we list basic specifications for the system that follow from these requirements as well as from aspects of the TPC and front-end electronics design. In Section 4.2 we introduce a conceptual data acquisition architecture, and briefly summarize its main features. In Sections 4.3 through 4.7 we provide some detail on possible implementations for the various TDAQ subsystems.

4.1 Requirements and Specifications

The requirements are summarized here:

1 subject 1

1.1 blah blah

1.2 blah blah

2 subject 2

2.1 blah blah

4.2 Reference Data Acquisition Architecture Summary (WBS 1.5.5.2)

The reference design of the data acquisition system is summarized in block diagram form in Fig blah. The components are described briefly in the following subsections. Each topic is described in more detail in subsequent sections.

4.2.1   Data transfer to and from cold electronics

4.2.1.1   Optical receivers

4.2.1.2   Data unpacking (demuxing and zero suppresion)

4.2.1.3   Slow control signals

4.2.2   Event building and triggering functions

4.2.2.1   Timing System

4.2.2.2   Physics Triggers

4.2.2.3   Event Model

4.2.3   Run Control

4.2.4   Slow Control

4.2.5   Infrastructure

4.2.5.1   Networking

4.2.5.2   Data Archiving

4.3   Data transfer to and from cold electronics (WBS 1.5.5.3)

data transfer

1 **4.3.1   Optical receivers**

2 **4.3.2   Data unpacking (demuxing and zero suppresion)**

3 **4.3.3   Slow control signals**

4 # 4.4   Event building and triggering (WBS 1.5.5.4)

5   event building

6 **4.4.1   Timing System**

7 **4.4.2   Physics Triggers**

8 **4.4.3   Event Model**

9 # 4.5   Run control (WBS 1.5.5.5)

10 # 4.6   Slow control systems (WBS 1.5.5.6)

11 # 4.7   TDAQ Infrastructure (WBS 1.5.5.7)

12 **4.7.1   Networking**

13 **4.7.2   Data Archiving**

5 Photon Detector (WBS 1.5.7)

Blah blah intro on Photon Detector

5.1 Requirements and Specifications

Blah blah on Photon Detector Requirements and Specifications.

5.2 Photon Detector Prototype (WBS 1.5.7.2)

5.2.1 Requirements and Specifications

Blah blah on Photon Detector Prototype Requirements and Specifications.

5.2.2 Description

Blah blah on Photon Detector Prototype Description.

5.3 Photon Detector Optics (WBS 1.5.7.3)

5.3.1 Requirements and Specifications

Blah blah on Photon Detector Optics Requirements and Specifications.

5.3.2   Description

Blah blah on Photon Detector Optics Description.

5.4   Photon Detector Devices (WBS 1.5.7.4)

5.4.1   Requirements and Specifications

Blah blah on Photon Detector Devices Requirements and Specifications.

5.4.2   Description

Blah blah on Photon Detector Devices Description.

5.5   Photon Detector Infrastructure (WBS 1.5.7.5)

5.5.1   Requirements and Specifications

Blah blah on Photon Detector Infrastructure Requirements and Specifications.

5.5.2   Description

Blah blah on Photon Detector Infrastructure Description.

5.6   Photon Detector System Checkout (WBS 1.5.7.6)

5.6.1   Requirements and Specifications

Blah blah on Photon Detector Checkout Requirements and Specifications.

5.6.2   Description

Blah blah on Photon Detector Checkout Description.

6 Veto

FIXME: *Text largely stolen from the Depth Document*

The most important reason for locating sensitive detectors deep underground is to eliminate the background events caused by cosmic ray muons that originate in the atmosphere of the Earth. Muons are the most numerous cosmic ray charged particles at the surface of the Earth. They are produced in the upper atmosphere by the collision of cosmic ray primaries (protons, and nuclei); and they lose about 2 GeV in the atmosphere before reaching the surface.

Only muons and neutrinos penetrate to significant depths underground. The muons produce tertiary fluxes of photons, electrons, and hadrons. The goal of the underground laboratory is to reduce all such sources of backgrounds by shielding the detectors under rock. The shielding is commonly expressed as either ft of standard rock (with density of 2.65 gm/cc) or in meters-waterequivalent (mwe). As muons penetrate underground they lose energy by ionization and by radiative processes.

xxx Stick table 1 of the depth document here.

6.1 Depth Requirements for Physics

6.1.1 Accelerator Neutrinos

The high granularity of the detector will allow removal of cosmic muons from the data introducing a small ($<$0.1%) inefficiency to the active detector volume, so that most of the accelerator induced events are unobscured. The rate of muons in the detector at the 800 level is xxx kHz. The drift time of the TPC is 1.6ms and we propose to to acquire data for one drift before and after the arrival of the beam signal, resulting in a live time of 4.8ms. During this time, xxx cosmic rays will pass through the active volume of the detector, resulting in a timing rejection factor of xxx 10^n. If a cosmic ray muon (photon) event mimics a contained in-time neutrino event it will be rejected based on pattern recognition.

In summary, a cosmic ray veto is not required to study accelerator neutrino interactions.

6.1.2 Nucleon Decay

The depth requirement for proton decay experiments is dominated by the livetime loss due to event overlap with cosmic ray muons. A liquid argon detector will have much less deadtime loss at shallow depths than a water cherenkov detector as the fine segmentation in space and drift time allow one to exclude regions of the detector around each passing muon. Bueno et al.[12] estimate an effective loss of detector mass of less than 4% for a 100 kT liquid argon detector with mountainous overburden of only 200 m with the use of a veto.

The most serious source of nucleon decay background for the νK^+ mode are K^0_L mesons produced by cosmic ray spallation in the rock surrounding the detector. These neutral kaons may enter the detector and produce a K^+ via charge exchange.

Add some text here explaining that a LAr TPC has good sensitivity to this channel. xxx

The veto described in the following section is designed to reduce the background in the νK^+ mode to a negligible level.

6.1.3 Solar Neutrinos

Add some text here if it is necessary.

6.1.4 Supernova Burst Neutrinos

Add some text here if it is necessary

6.1.5 Supernova Relic Neutrinos

Add some text here if it is necessary

6.2 Veto Description

The system consists of two "Hell Raiser" side vetos along the length of the detector and two, more conventional, veto systems at each end of the detector.

¹ The Hell Raiser veto consists of a matrix of holes drilled into the walls of the cavern as
² shown in Figure xxx. The holes extend from the central detector cavern to the side galleries.
³ A pipe containing liquid scintillator and wavelength shifting fiber is installed in each hole. The
⁴ hole configuration is designed to provide the highest tagging efficiency for muon angles with the
⁵ highest rate (vertical). The optical fiber readout system is adopted from the Nova experiment.

⁶ Description of the efficiency here. xxx

⁷ A conceptual layout for the end veto detectors is shown in Figure xxx. These are conven-
⁸ tional, high efficiency, particle tracking detectors. We assume that these are liquid scintillator
⁹ detector modules similar to those developed for the Nova experiment.

¹⁰ A description of the DAQ for the veto system goes here.

7 Installation and Commissioning

Design and construction of detector components are described in the system sections. The detector systems are responsible for transport of components and sub-systems to the far detector site. The Installation and Commissioning system is responsible for all LAr20 related activities at the far detector site. This model has been chosen to foster close coordination with other activities at the far detector site. Close coordination is also required between the I&C system and the provider systems. The I&C manager therefore has an exceptional integration role and has broader authority than the other sub-system managers.

Commissioning extends beyond the completion of the LAr20 project. On-project commissioning activities include 1) the coordination of all system checkout activities, culminating in the approval to introduce liquid argon into the detector, and 2) the managing the steps required to meet the CD-4 goals.

The responsibility and authority for the design, installation and use of the detector quiet power distribution and detector grounding system is held by the integration engineer. All attachments to the detector that create an electrical connection are done under the oversight of the integration engineer. The integration engineer has oversight responsibility for all electrical and electronics design and installation tasks. (I'm not sure that this belongs here...)

7.1 Requirements and Specifications

The installation requirements are defined to a large extent by the DUSEL requirements for experiments document (DUSEL note #56 I think). We will also need space, temperature, humidity requirements for storage. All detector components will have been cleaned and tested before they are shipped. They will be visually inspected for damage that may have occurred during shipment. Final testing of components will be done during installation underground (I think).

Some requirements go here to specify the state of the cavern when this activity begins. I assume for now that the concrete liner will be provided by WBS 1.6.

7.1.1   Installation Prototype

It isn't yet clear that an installation prototype is required so this section may be deleted. A prototype will only be necessary if installation is a significant cost driver or if there is a significant need for mechanical integration.

7.1.2   Above-ground Installation Activities

7.1.2.1   Surface Storage Facilities

Detector components will be delivered to DUSEL over a period of several months. The cryostat insulation will comprise the largest bulk of material; approximately 5500 m^3. TPC wire frames will be shipped in special sealed shipping containers. All shipping containers will be logged in a database when they arrive and will be stored in a surface storage building. (Crappy language)

Suitable storage space will be identified at DUSEL. The terms for the use of this space will be negotiated with DUSEL and documented in a MOU.

7.1.2.2   Cryogenics Receipt and Storage

The most efficient means of delivering 20kton of liquid argon to DUSEL is by rail transport. Unfortunately, the rail lines to Lead, SD were decommissioned several decades ago, leaving truck transport as the only option. Mixed rail-truck delivery with a transfer in Spearfish, SD is not cost effective. (This text belongs in the cryogenics system section)

Delivery of liquid argon will occur over a 4 - 6 month period of time with approximately 8 tank trucks/day arriving on site. Each tank truck will have been loaded with 18.8 Tons of LAr but minor losses will occur during shipment. Transfer of the liquid argon out of the tank truck will require 1 hour, including the time for making hose connections, purging hoses, etc. As described in section xxx, the liquid argon purity is tested by the vendor before the truck departs for DUSEL. The purity is checked again during unloading. The partially emptied tank truck will be returned to the vendor if the purity is found to be > 5 ppm.

Some text will go here describing where the liquid argon is stored temporarily. The options are above ground in a storage tank, underground in the detector or underground in a storage tank.

Some text will go here describing the construction method planned for temporary storage. The most likely is that we would have a design and build contract.

7.1.3 Below-ground Pre-Installation

Additional infrastructure is required within the underground cavern after the project receives beneficial occupancy. This infrastructure includes detector access structures, telephone communications, computer networking, facility monitoring, sign-age and cavern access controls.

Some text may go here describing training for the installation crews.

7.1.4 Below-ground Installation Activities

Detector installation will take place in four phases: cryogenics plant construction, cryostat construction, detector installation and cryostat cleaning and cool-down.

7.1.4.1 Cryogenics Plant Construction

The principal items of cryogenic plant will be assembled and tested off site at the supplierâĂŹs facilities. They will be disassembled to facilitate delivery to site and for transportation to the cavern utilising the available lift shafts. The units will be transported from the lift shaft to the equipment hall within the underground cavern and will be reassembled. Precommissioning and on site testing ahead of the introduction of cryogens will confirm their fitness for service.

Equipment located within the cryostats such as reticulation pipework and pump wells will be installed following completion of the membrane. The equipment will be installed ahead of the membrane leak test so that the test can confirm that the fit out of the cryostat has not compromised the containment system.

7.1.4.2 Cryostat Construction

The membrane cryostat is constructed using a pre-installed bridge crane with only top-down access to the pit floor. The pre-fabricated roof structure is installed prior to the GTT insulation/membrane build-up within. The TPC is constructed insitu in a scaffold-like manner from individual frames lowered through a roof hatch. The roof hatch is sealed on completion. All construction materials are transported to the cavern via the Yates Super cage or via the dedicated access shaft.

The construction sequence will proceed as follows:

1.

2. Complete cavern including drainage system to sump and 20t bridge crane

3. Complete concrete liner base slab (includes installation of heating ducts)

4. Install end and side walls in successive lifts (includes installation of heating ducts)

5. Form and install corbel (includes completion of heating ducts and upper cast-ins)

6. Welded roof modules transported to cavern in two sections. Individual sections are under-slung from the Yates Super cage.

7. Infill roof steelwork and bracing transported to cavern in pieces (via Yates Super cage)

8. Welded roof modules and infill roof sections successively installed from far end using bridge crane. This includes welding of the steel plate (vapor barrier). Provision for a large access hatch in end welded roof module

9. Post-tension side walls

10. Apply vapour barrier to base slab, side and end walls

11. Installation of heating system throughout concrete elements and associated control units.

12. Insulation and membrane build-up on base, walls and underside of roof (supervised by GTT). Undertake ammonia leak test and any remedial works. Cleaning of inner membrane surface.

13. Install rails and internal piping within cryostat

14. 7x4m TPC frames transported to cavern underslung from the Yates Super cage. Frames are individually lowered through the access hatch using the bridge crane, assembled together within tank and positioned on internal rails. Assembled TPC units are moved to final position by hand and locked in place at base (by FNAL).

15. Install cryogenic plant and associated pipework within cavern

16. Final commissioning of TPC electronics prior to sealing of roof hatch

Material	Quantity	Comment
Structural steel roof	260 te	Carbon steel
Concrete liner	2500 m^3	Reinforced/Post-tensioned
Heating system cable length	5100 m	Thermion (or similar)
Insulation/membrane	5500 m^2	GST by GTT (or similar)

7.1.4.3 Detector Installation

Here is where we describe the TPC assembly sequence.

7.1.4.4 Cryostat Cleaning & Purging

The cryostate cleaning and purging procedure is described here. I am assuming that no cryogens will be introduced to the detector prior to commissioning. Some thought needs to be given to the optional LAr storage system and how this system would be approved for use with cryogens.

7.1.5 Detector Commissioning

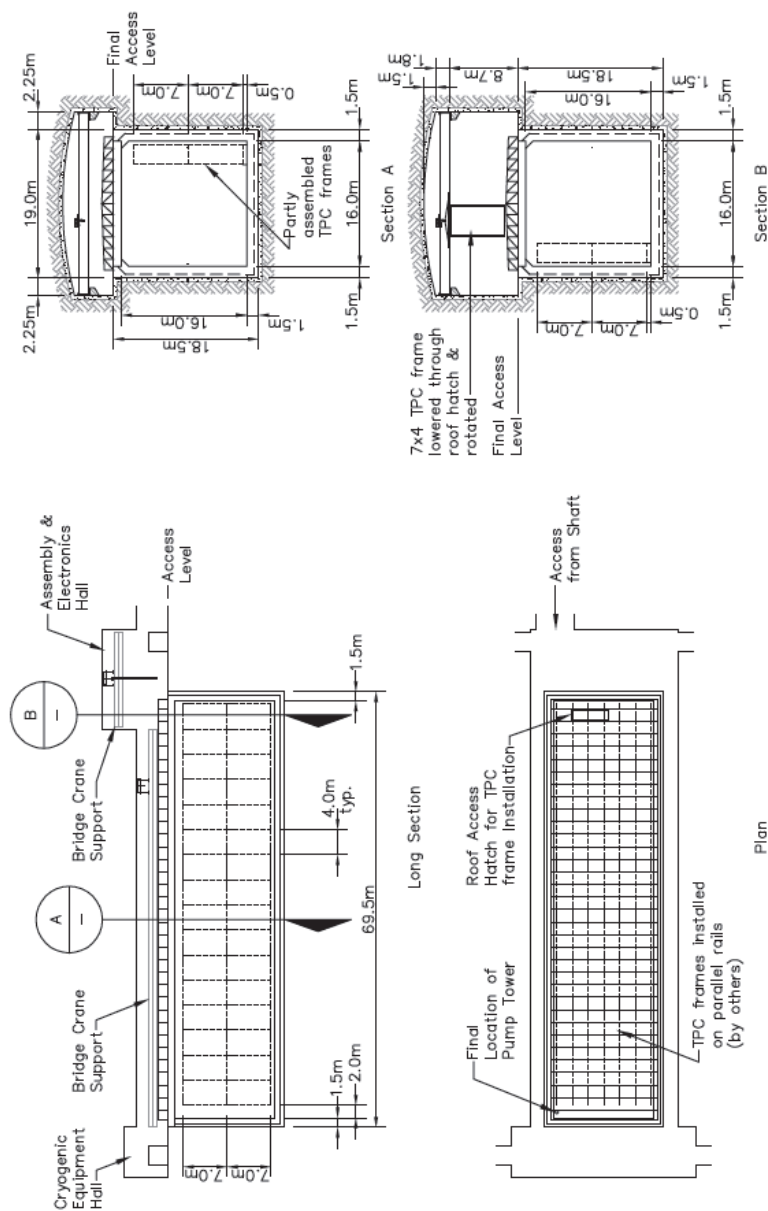We need to have an idea of the CD-4 goals before this section can be written.

Fig. 7.1. TPC Installation scheme

8 Alternatives

Alternative detector configurations and design parameters are discussed in this chapter.

8.1 Detector Configuration

8.1.1 Double Phase Readout

The European GLACIER collaboration is pursuing a novel double phase readout detector technology that has potential advantages. In this scheme, ionization electrons are drifted upwards under the influence of an electric field towards the liquid-vapor interface. The electrons are extracted from the liquid into the vapor by an electric field of 2.5 kV/cm. The electrons then drift to two stages of Large Electron Multipliers (LEM). Electrical signals are induced on segmented electrodes on the LEM.

This method requires far fewer readout channels than the preferred design, however significant R&D is required to demonstrate the viability of this technique for a large detector. This design requires very long electron drift lengths ($\sim$20m) in order to be cost effective.

8.1.2 Cryostat Shape

Storage tanks can be classified by shape (upright cylinder, horizontal cylinder, rectangular parallelepiped) and means of support (self supporting, externally supported).

A horizontal cylindrical tank would require significant structural support to withstand the gravitational load. On the other hand, upright self-supporting cylindrical tanks are commonly used for surface storage of cryogenic liquids. The proposed above ground LAr TPC experiment FLARE utilized a tank of this configuration. An upright cylindrical tank is also proposed for the 100 kton GLACIER underground detector. In contrast, the 600 ton ICARUS detector is a rectangular parallelepiped.

A study was performed to compare the cost for three configurations of equivalent active mass: upright cylindrical cryostat (soup can), rectangular parallelepiped externally-supported cryostat (membrane) and the rectangular parallelepiped self-supporting cryostat (modular). The study considered the cost of rock excavation, the cost of the total inventory of LAr required for a detector for an "active mass" of 16.7 kton and a rough estimate of the cryostat cost. The "active mass" is defined as the volume of LAr that is sampled by the readout electronics. (Note that the "fiducial mass" of the detector is less than the "active mass".)

The active/total mass fraction for the three configurations varies between 70% and 74% and is therefore not a significant factor in the cost difference. The major cost factor is the volume of rock that must be excavated for these configurations. There is a significant amount of unused cavern space if an upright cylindrical tank is located within a rectangular parallelepiped cavern. The amount of unused space can be reduced by excavating a cylindrical cavern but the excavation cost would increase significantly ($\sim$30%).

The study results show a cost range of 10% - 20% for the different configurations. This is within the uncertainty of the estimates ($\sim$50%) so none of the options can be rejected purely on economic grounds given our current state of knowledge. Given sufficient resources, all configurations could be more fully developed to make a more informed decision however any potential value would be offset by the cost of pursuing multiple design paths.

The study results also indicate that a membrane cryostat is the most cost effective solution. It clearly maximizes the use of the excavated rock volume. A membrane cryostat is also inherently more cost effective that a self-supporting cryostat since the hydrostatic pressure of the liquid is constrained by the cavern walls and not the cryostat walls, thereby reducing the amount of structural steel required.

8.1.3   Modular Cryostat

The modular LANNDD detector concept is a viable alternative to the preferred design. The detector, shown in Figure xxx, consists of a cubic matrix of drift cells.

FIXME: *Include lots of text from the Ref Design 1b document*

8.2   Depth Options

8.2.1   300 level

This section should describe the physics and cost issues for the 300 level

8.2.2   4850 level

This section should describe the physics and cost issues for the 4850 level

8.3   Cryogenics Plant

FIXME: *Alternatives considered by Arup are in Chapter 2. They should be moved here.*

8.3.1   Refrigeration

8.3.2   LAr Storage

It is desirable to provide temporary storage of liquid argon to decouple the delivery schedule from the detector construction schedule. Ideally, temporary storage could reduce the LAr20 schedule by 6 months since argon deliveries can occur in parallel with detector construction. This is only possible if construction of the temporary storage facility occurs concurrently with other activities.

Temporary storage also mitigates the risk of a detector failure necessitating access to the cryostat. If this occurred and temporary storage were not available, the argon would be vented to the atmosphere and the $25M investment of LAr would be lost.

FIXME: *Stick the Arup NPV calculation in here somewhere*

A rough estimate for the cost of above-ground LAr storage and associated infrastructure is ~$25M. This estimate was found independently by Arup and by application of a cryogenic tank cost scaling formula given in lbne-docdb #54.

It would be advantageous to provide underground LAr storage in a cryostat that has the same configuration as the detector cryostat. This second cryostat could be converted into a second detector in the future. The cost of this option is explored below.

FIXME: *Need costing information from Arup to complete this section. We have something from Jacobs already*

8.4 Cryostat

8.4.1 Insulation

Describe the pros and cons of passive vs active insulation. Can use the results of the May 17 mini-review here.

8.5 TPC

8.5.1 TPC Configuration

8.5.1.1 Reference Design 1a

Reference Design 1a relies on a minimal extrapolation of the MicroBooNE TPC module design. The detector would be installed in a cavern with drive-in access and would consist of a rectangular stack of TPC modules that have been constructed above ground.

CD-1 level cost and schedule information is available for the MicroBooNE TPC module. A modest extrapolation of the module design parameters will not introduce large cost uncertainty if done properly. The extrapolations are in dimensions that do not challenge the limits of the technology. For example, the result of increasing the width of the MicroBooNE TPC wire frame size will increase the length of the longest wire and increase the number of wires by a small amount. The increased capacitance due to longer wire lengths will increase the electronics equivalent noise charge, but the signal to noise level will remain above the minimum required. The drift distance of this Reference Design is the same as that of MicroBooNE TPC module (2.5m) since additional R&D would be required to demonstrate that a longer drift is feasible.

The technical requirements for this reference design are determined in part by the construction model. We assume that the construction steps are as follows:

1. Fabrication of components and sub-assemblies at vendors, universities and national labs and shipment to DUSEL.

2. Final assembly of TPC modules in a surface building at DUSEL.

3. Transport of the TPC modules by truck to the cavern.

4. Rigging of the TPC modules into the cryostat using a cavern crane.

The height of one TPC module is determined by the minimize size constraint of these steps. The limit is found to be ∼7m. The limiting factor is the maximum transverse size for an economical access drift into the cavern. Each LAr20 TPC module would be constructed similarly to ICARUS; with the cathode plane in the middle and anode wire planes on each side. Figure 8.1 shows the detector concept consisting of 42 TPC modules arranged in a stack 3 wide x 2 high x 7 deep.

This detector configuration suffers from a poor fiducial/total mass fraction. Only 56% of the LAr in the detector is useful for physics. The cost of this TPC design is ∼3x the cost of the preferred design.

8.5.1.2   Reference Design 2a

Reference Design 2a is similar to the preferred design. The major difference is the use of room temperature accessible electronics. The concept is shown in Figure 8.2.

Short low-impedance cables route wire signals from the Anode Plane Assemblies (APA) to a cold feedthrough which is kept at ∼120K. The readout electronics are located within the feedthrough. The benefit of this design is that the electronics boards can be replaced without removing LAr from the detector.

There are a number of disadvantages to this concept however. The cable lengths must be kept to ∼1m, the wire spacing must be increased to 5mm and the wire angle reduced from 45° to 30° in order to achieve a marginally acceptable signal to noise ratio. As a result, the track resolution in the vertical direction is ∼1cm. A large number of feedthroughs are required in order to keep the cable lengths short. One feedthrough containing 576 electronics channels is required for every 53cm along the top of each APA. Each feedthrough would be 34cm x 22cm in cross section and would be ∼2m long.

8.5.2   Wire Spacing

There is a clear benefit to having the smallest wire spacing possible. The distinguishing feature of the LAr TPC is the ability to distinguish one MIP electrons from 2 MIP electron-positron pairs close to the interaction vertex. A wire spacing smaller than the preferred design (3mm) would have smaller Signal-to-Noise ratio (S/N) commensurate with the wire spacing. The design S/N ratio could be restored by decreasing the noise. The most direct means of accomplishing this would be to reduce the wire length, thereby increasing the number of electronics channels. Reducing the wire spacing below 3mm will only offer minimal return since the background from NCπ^0 events is already quite small (∼1%).

We now explore the cost savings by increasing the wire spacing from 3mm to a larger value

(5mm). This is a reasonable value engineering option to consider if the savings are significant. A study of the detector cost estimate shows that the dominant factors are the incremental cost for the electronics readout and the labor required to wind the wires.

The electronics readout cost defined here includes design labor, IC masks, ASIC chips, boards, cables, cryogenics feedthroughs and cold testing. The electronics cost can be split into fixed and incremental costs and can be parameterized as \$3.7M fixed cost + \$4.60/channel incremental cost. These costs are fully burdened without escalation or contingency.

The incremental labor cost to wind the detector wire planes is \$0.9M for three wire planes with a 3mm wire spacing, or \$1.50/wire.

In total, the incremental cost of adding one wire of readout is \$6.10. The cost of the LAr20 detector could be reduced by ~\$1.6M by increasing the wire spacing to 5mm. This is <1% of the LAr20 Total Project Cost. We judge that the potential benefit of having the highest possible granularity greatly outweighs the cost savings.

8.5.3 Number of Wire Planes

The results of the cost exercise described in the previous section can be applied to the question of the optimal number of wire planes.

The preferred design includes three instrumented wire planes and one un-instrumented grid plane. Reducing the number of instrumented planes to two would reduce the detector cost by ~\$1.3M with a minor loss of ν_e identification efficiency. This would also reduce the readout redundancy however and potentially affect the long term reliability of detector operations. We do not consider this a credible value engineering option.

The un-instrumented grid plane could be eliminated, saving ~\$1M. As described in section xxx, the grid plane is used to create equal signal levels in both induction planes. The signal level in the first induction plane would be reduced by ~2x if the grid plane were eliminated. We do not consider this a credible value engineering option.

8.5.4 Drift Length

As shown in Figure 8.3, an electron lifetime of ~5ms will result in a 25% loss of signal for a 2.5m drift.

The specification of the 2.5m drift is based on a judgment that considers experience from historical and currently operating detectors and test stands and the purification techniques used to achieve an acceptable lifetime.

An electron lifetime of 10ms is routinely achieved on the Fermilab Materials Test Stand. The ICARUS detector is now in operation and has achieved a lifetime of xxx ms. The Liquid Argon Purity Demonstrator (LAPD) will (has?) achieved a lifetime of xxx ms without relying on vacuum evacuation for initial cleaning.

LAr20 R&D includes a study of argon purity in the 30 ton membrane prototype. The LAr20 2.5m drift length specification will be revisited when this R&D is completed. A longer drift length may be specified in the future as a value engineering option if the R&D results are supportive.

8.6   Trigger & DAQ

We need to define the Trigger DAQ first...

8.7   Installation & Commissioning

8.7.1   Drive-in/Shaft Access

We can't write this section until we have made a decision on the preferred option.

FIXME: *More thought needs to go into alternatives...*

8.8   Photon Detection

Photon detection is not required to address the primary scientific goal of LBNE - the study of accelerator neutrino oscillations. A beam signal from the accelerator complex is sufficient to reduce cosmic ray backgrounds to a negligible level.

Photon detection is also not required for non-accelerator physics studies if data is read continuously from the detector. **FIXME:** *Mention the resulting data rate at the 800 level here?*

There is no ambiguity about the location of an event in the detector if at least one track crosses an interior cathode plane. The transverse position of an event is unknown if it is fully contained within one drift cell and there is no photon detection to define the event time. It is impossible to determine if the event is fully contained if the event occurs in the drift cells at the edge of the detector however. As a result, the edge cells cannot be used for non-accelerator physics studies, reducing the fiducial mass by 33%. The photon detection system allows the entire fiducial mass to be utilized for these physics analyses.

Most LAr TPC's use TPB coated PMT's to detect scintillation light. Light emitted more than a few meters from a PMT is not detectable however due to Rayleigh scattering, so PMT's would need to be placed between drift cells. This configuration is not readily compatible with the anode plane assembly concept. Conceptually, each interior cathode plane can be replaced with two cathode planes separated by sufficient space for an array of PMT's. This would increase the width of the detector and the cavern by ∼1m and result in a lower fiducial mass.

A variety of options were considered for the wave length shifting scheme and the light guides. These options suffer from lower light collection efficiency and result in higher cost for the same performance.

8.9 Veto

The original veto concept shown in Figure 8.4 is a more conventional option than the preferred design. The 3m width of the veto panels shown in the figure requires a 31m cavern span which would require significantly more roof support and rock excavation, and thus higher cost, than the preferred design.
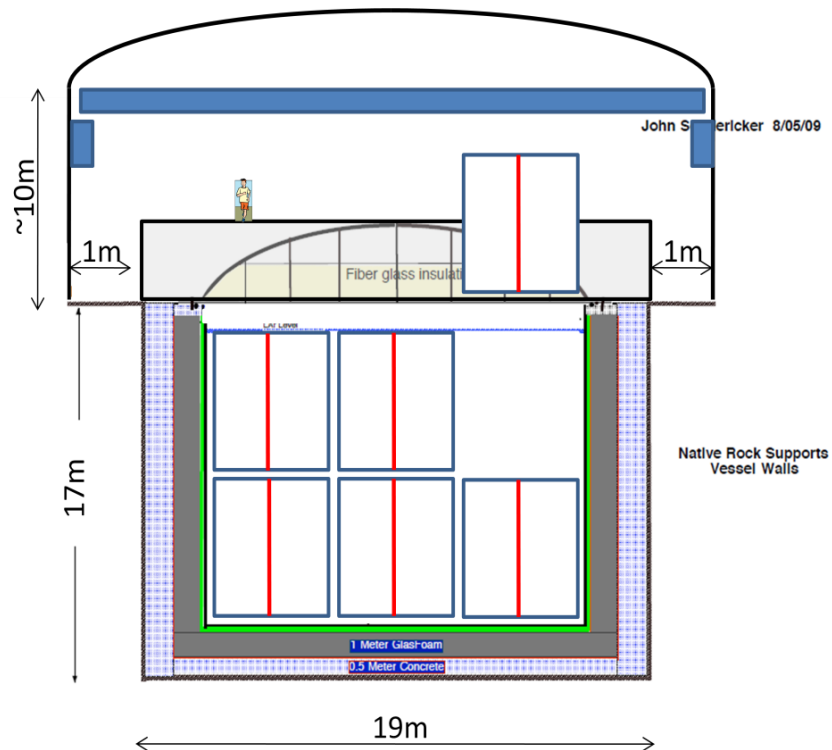
Fig. 8.1. Reference Design 1a cryostat pit and cavern concept showing one 5m x 7m TPC module as it is being rigged into position. Cathode planes are shown in red.
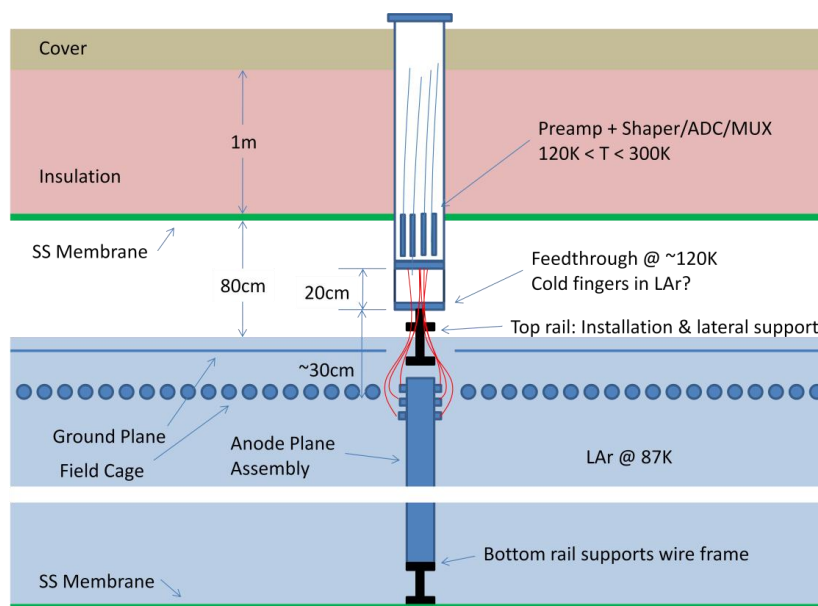
Fig. 8.2. Reference Design 2a, showing cable routing from an Anode Plane Assembly to a cold feedthrough. The warm readout electronics are located within the feedthrough.
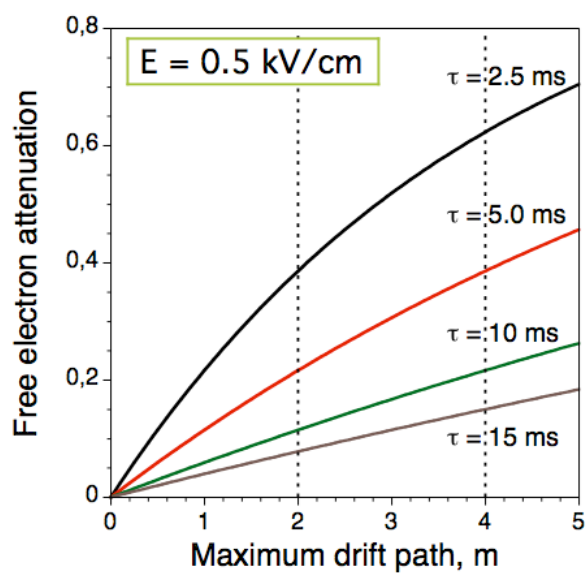
Fig. 8.3. Signal attenuation vs electron lifetime and drift distance
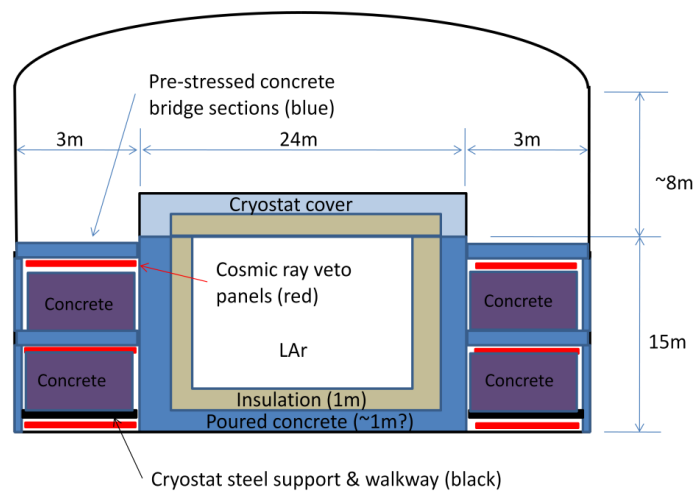
Fig. 8.4. Alternative veto concept

9 Value Engineering

text

10 Environment, Safety and Health

FIXME: *Text from the Arup report*

The proposed cryostat and the associated cryogenic systems form a unique facility which must be subject to rigorous health, safety and environmental assessments as part of the design, engineering, construction, commissioning and operation phases.

As with many unique projects this facility will apply extensive experience gained on similar previous projects. In particular,

- Fermilab has extensive experience with working L.Ar in a laboratory environment, albeit at a smaller scale

- Fermilab has 8 years of experience with the development and operation of underground laboratories such as the NuMI facility at Fermilab and the MINOS detector in Soudan, MN

- The engineering and construction industry has experience of the fabrication of very large cryogenic storage tanks (LNG storage tanks to $185,000 m^3$)

- the mining industry has experience of working underground,

The challenge with this project is to ensure that all of this relevant experience is applied

10.1 Construction

The processes involved in the construction of the cryostat have been extensively developed over many years, The execution of this project will be of interest to large multinational engineering contractors who are experienced in the management of this type of construction work and in the management of the associated hazards. Specific construction hazards that will need to be managed will include:

○ Working at height using scaffolding or bespoke access systems. A typical access system for membrane storage tank construction is detailed in the proposal received from GTT.

○ Materials handling with limited access and restricted height

○ Large numbers of vehicle movements associated with the delivery of personnel and materials and the execution of the works

○ Multi trade working

○ Segregation of controlled activities (weld inspection, hydrotest etc)

10.2   Underground Cryogenic Storage Tanks

There is limited experience of large scale underground construction of cryogenic storage tanks. In ground tanks that have been constructed have been designed to be installed in surface excavations. Specialist advisers will be retained to address issues such as:

○ Personnel transport underground during normal access and egress including access control systems

○ Emergency systems (lighting, drainage, HVAC)

○ Emergency procedures

○ Control of hazardous operations that may impact on ventilation systems

○ Restricted plant access and maneuvering space

○ Confined working

Health and safety during construction is a key concern, especially for underground work. During the screening process a number of issues were identified and used to steer the selection/design. Examples, which are described more fully in the proceeding sections, include the need for more than one ingress/egress point to all work areas and the need for containment of Hydrogen Sulfide emissions during glass foam cutting increasing the difficulty of using this material.

10.3   Commissioning and Operation

The principal operational concern is the risk of asphyxiation due to a release of argon. Any inadvertent discharge of L.Ar within the cavern will result in a significant ODH.

Argon is a colorless, odorless gas that is heavier than air and will therefore displace oxygen to generate an Oxygen Deficiency Hazard. Argon is an inert gas and therefore does not present a flammability or explosion risk.

The cryostat and associated cryogenic plant forms a single closed process plant. A determining tenet of the design Is the containment of argon and the exclusion of contaminants from the argon inventory. There are no operations or processes to be undertaken that would result in the release of Argon under normal circumstances.

The operation of the facility should be controlled by formalised procedures covering normal operations, upset conditions and emergencies. Plant control operation should be undertaken by a dedicated team of trained and experienced operatives who are fully conversant with the plant operating instructions and procedures.

Strict management control systems should be in place to audit the operation of the facility.

It is understood that free access will not be provided to the underground caverns. Access will be controlled by a strict permit to work system that recognizes the hazards associated with entering the caverns and that controls all activities that are to be undertaken.

10.4   Cryostat Design

The cryostat design is such that no connections or penetrations are provided below the maximum liquid level. This ensures that should pipework or associated equipment fail pumps can be switched off and the maximum release is then limited to the pipework volume. No liquid is released from the cryostat.

10.4.1   Containment

The liquid contaminant capabilities of the cryostat are comparable to those of cryogenic liquefied gas storage tanks used for storing products such as LNG, LPG and Ethylene. The level of containment provided by these tanks is defined in such codes as BS 7777, BS EN 14620 and NFPA 59A. BS EN 14620, the most recent code, defines three levels of containment:

- *Full Containment - A full containment tank shall consist of a primary container and a secondary container, which together form an integrated storage tank. The primary container shall be a self-standing steel, single shell tank, holding the liquid product. The primary container shall either be open at the top, in which case it does not contain the product vapors or equipped with a dome roof so that the product vapors are contained.*

— *The secondary container shall be a self-supporting steel or concrete tank equipped with a dome roof and designed to combine the following functions:*

    ∗ *in normal tank service: to provide the primary vapor containment of the tank (this in case of open top primary container) and to hold the thermal insulation of the primary container;*

    ∗ *in case of leakage of the primary container: to contain all liquid product and to remain structurally vapor tight. Venting release is acceptable but shall be controlled (pressure relief system).*

— *The annular space between the primary and secondary containers shall not be more than 2.0 m.*

  ○ *Double Containment - A double containment tank shall consist of a liquid and vapor tight primary container, which itself is a single containment tank, built inside a liquid-tight secondary container. The secondary container shall be designed to hold all the liquid contents of the primary container in case it leaks. The annular space, between the primary and secondary containers, shall not be more than 6,0 m.*

  ○ *Single Containment - A single containment tank shall consist of only one container to store the liquid product (primary liquid container). This primary liquid container shall be a self-supporting, steel, cylindrical tank. The product vapours shall be contained by:*

— *either the steel dome roof of the container;*

— *or, when the primary liquid container is an open top cup, by a gas-tight metallic outer tank encompassing the primary liquid container, but being only designed to contain the product vapours and to hold and protect the thermal insulation.*

The membrane cryostat by virtue of the primary steel membrane and the secondary polymeric barrier within the insulation are able to provide full containment.

A modular cryostat design provides double containment with the cavern pit providing the secondary containment. A failure (significant leak) of the primary barrier in the modular cryostat will result in a release of argon and a subsequent ODH in the cavern. However, the primary barrier is manufactured from high quality 9% nickel steel, is tested during construction and is of robust design and construction. The probability of failure is therefore low.

The primary barrier in the membrane cryostat is manufactured from thin flexible sections of stainless steel plate. This is inevitably less robust than the primary barrier within the modular cryostat. However the design of the barrier system and high quality control during construction has resulted in an excellent service performance with only anecdotal evidence of pin-hole leakage which was understood to have been detected during testing. A failure of the primary barrier in the membrane cryostat will not result in the release of argon.

A published risk assessment of a pilot plant for underground storage of LNG utilizing the GTT membrane cryostat has estimated that the probability of failure is approximately once in 110,000 years. XXX REF GEOSTOCK.

Hence the modular cryostat has a low probability of primary barrier failure but a high resulting consequence whereas the membrane system may have a slightly higher probability of failure but with reduced consequences.

10.5   Cryogenic Systems Design

The cryogenic systems are generally proprietary items of equipment that are proven and reliable. Large inventories of pressurized fluids and gases are not included and the cryostat contains multiple levels of gas and liquid containment.

Isolation valves are provided on all cryostat nozzles so that the cryostat can be fully isolated if necessary. Redundancy is included such that any leaking line can be isolated whilst still maintaining the integrity of the cryostat and the pressure protection system. The use of remotely actuated isolation valves will be considered to avoid the need for personnel intervention within the cavern following a release.

10.6   Maintenance

A program of scheduled maintenance will be developed for the cryostat and all of the associated cryogenic systems. The requirement to undertake maintenance that could result in the exposure of personnel to the asphyxiating hazard has been minimized.

The majority of the cryogenic plant has been located outside the access portal. Equipment remaining in the cavern is either located within the cryostat (circulation pumps) or is benign plant (re-condenser vessel) with minimal long term maintenance requirements.

The design of the cavern will include the following facilities to ensure the safety of personnel entering the caverns:

- Ventilation

- Oxygen level monitoring

- Lighting

- Remote monitoring of personnel and activities

○ Access control

All activities within the cavern and in particular those involving maintenance on or working in close proximity to argon filled equipment will be controlled by a Permit to Work system.

Emergency escape and rescue procedures and the necessary facilities will be provided. These may include but should not be restricted to:

○ Breathing Apparatus

○ Air tight safe refuges with independent air supplies

○ Trained rescue and recovery personnel

○ Alternative means of escape.

10.7   Analysis

A preliminary Failure Modes and Effects Review has been carried out. The Review covered the cryostat tank and mechanical plant, under operating conditions. The review did not include the following aspects:

1. purifiers

2. electrical systems and security of supply

3. the cryostat fill and empty sequence

4. commissioning activities

The review focused on those failures mechanisms that would result in the release of either gaseous argon or liquid argon as the release of argon was deemed to be the most significant hazard.

The review noted that, for all options, the fundamental containment was the cryostat, that all penetrations were above the maximum liquid level and that every penetration of the containment would be valved so that whatever the state of the plant and the need for repair work, the main inventory of L.Ar could be isolated.

All mechanical plant required during normal operations has been provided on a duty-and-standby (a minimum of 100% redundancy) basis.

There are predictable maintenance and repair operations for which, in the detailed design, provision will be needed to isolate and purge elements of the plant, bring them to room temperature, and opening them up for work without either contaminating the L.Ar stream or endangering the maintenance personnel.

The review concluded that appropriate arrangements had been made to contain the cryogenic liquids and protect the operational and maintenance personnel, for a concept stage of the design. A summary of the review is shown in the following table:

FIXME: *Text from MicroBoone's CDR section 4.2.7 follows here. Do something with it.*

The use of liquid argon makes the MicroBooNE (LBNE far detector?) site a potential oxygen deficiency hazard (ODH) area. The area will be analyzed and classified according to Fermilab (DUSEL?) ODH standards. Based on the results of that analysis, appropriate ventilation, oxygen sensors, alarms, signs and training will be implemented. Besides the indoor spaces normally covered under the Fermilab (DUSEL?) standards, potential outdoor problems will also be studied. It will also include a discussion of secondary containment, despite the absence of national standards requiring secondary containment for liquid argon storage.

The liquid nitrogen and argon are also extremely cold and can cause frostbite if they come in contact with skin. Individuals making connections between the delivery trucks and the system must wear protective equipment including gloves, aprons and face shields. Individuals working with the plumbing system must do so as well. There will be training provided and people will have to be qualified for tasks involving either ODH or cryogenic hazards as provided in the FESHM. Fermilab (DUSEL?) environmental safety and health standards will be followed in the design and implementation of the cryogenic system.

References (again, from microboone doc) [1] One example of such a company is General Plastics Manufacturing Co LAST-A-FOAM at www.generalplastics.com [2] http://lartpc-docdb.fnal.gov/cgi-bin/ShowDocument?docid=410 [3] G. Carugno at al., "Electron lifetime detector for liquid Argon" NIM A292 (1990), 580. and D. Finley et al., "Work at FNAL to achieve long electron drift lifetime in liquid argon." FERMILAB-TM-2385-E, Oct 2006. 9pp

DUSEL Cryo Tank and Plant		Failure Mode and Effects Review			April 12 201
System	Component	Failure Scenario	Consequence	Protection	Action/ Note
Membrane Structure	Membrane	Leakage through defect in construction	Loss of liquid Ar to insulation. Insulation effectiveness reduced. Ar leak to purge / vent system	Conventional detailing for cryogenic conditions from LNG experience. Construction of membrane includes leak tightness test as standard.	
Membrane Structure	Membrane	Leakage through contact with TPC – abrasion, corrosion	Loss of liquid Ar to insulation. Insulation effectiveness reduced. Ar leak to purge vent system	Designed interface between membrane & TPC to control contact forces and return of purified Ar to cryostat at low level to reduce turbulence and vibration	
Membrane Structure	Membrane	Leakage at pipe penetration of membrane	Loss of vapor Ar to cavern above cryostat; Possible entry of air to cryostat if internal pressure is below ambient	Conventional detailing for cryogenic conditions from LNG experience. Construction of membrane includes leak tightness test as standard.	

Fig. 10.1. Preliminary Failure Modes and Effects Analysis

11 Quality Assurance

This Quality Assurance (QA) Program was developed to support the Water Cherenkov Detector's (WCD) quest for quest for scientific excellence. The program leverages off DOE G 414.1-1B, Management Assessment and Independent Assessment Guide; DOE G 414.1-2A, Quality Assurance Management System Guide; DOE G 414.1-3, Suspect/Counterfeit Items Guide; DOE G 414.1-4, Safety Software Guide; DOE G 414.1-5 Corrective Action Program Guide, and the Baldrige Criteria for Performance Excellence. This program description also addresses the requirements of DOE Order 226.1A, Implementation of Department of Energy Oversight Policy (contractor assurance system). Using these consensus standards as tools in the development of this program ensures the delivery of a robust, process-based, integrated Quality Program and contractor assurance system.

11.1   Mission

11.2   Program

11.2.1   Organizational Structure

11.2.2   Management Processes

11.3   Personnel — Training and Qualification

11.3.1   Train Personnel

11.3.2   Provide continual training

11.4   Quality Improvement

11.4.1   Processes

11.4.2   Identify and Correct

11.4.3   prevention

11.5   Documentation and Records

11.5.1   Preparation

11.5.2   Specify and maintain records

11.6   Work Processes

11.6.1   Perform Work

11.6.2   Proper Use

11.6.3   Maintain

11.6.4   Calibration

12 Risks

A short introduction here that reminds the reader of the points made in the Major Risks section in Chapter 1.

A description of the overall risk management scheme will presumably reside in the LBNE volume so nothing will be required here.

12.1 The Integrated Plan for LAr TPC Neutrino Detectors in the U.S.

The integrated plan was developed to ensure that the risks associated with the construction of a large underground LAr TPC are well understood and that R&D currently underway is adequate to mitigate these risks. The plan considers the following activities:

- The Materials Test Stand at FNAL

- Existing electronics test stands at BNL and FNAL

- The Liquid Argon Purity Demonstrator (LAPD)

- The ArgoNeuT LAr TPC

- The MicroBooNE experiment

- The integrated software development effort (LArSoft)

The plan was developed by a group of people who have relevant experience in U.S. and European R&D activities: Bruce Baller, Flavio Cavanna (L'Aquila), Bonnie Fleming (Yale), Cat James , Ornella Palamara (Gran Sasso), Stephen Pordes, Rob Plunkett, Gina Rameika, Brian Rebel and Jon Urheim (Indiana). The group identified the "residual risks" that will remain after the currently envisioned R&D plan is completed by proposing a scenario where all of the currently planned R&D activities are successful:

○ ArgoNeut has completed taking data in the NuMI neutrino beam. Current indications are that it will achieve its R&D and physics goals.

○ The LArSoft group has completed work on a detailed Monte Carlo simulation and is actively developing reconstruction software. At the current pace of development, full 3D track and electromagnetic shower reconstruction will allow detailed physics studies to begin in late 2010.

○ First results from LAPD are expected in the summer of 2010. The group assumed that LAPD will successfully demonstrate the ability to achieve long electron lifetime without first evacuating the cryostat.

○ MicroBooNE is scheduled to begin operation in 2013. For the risk analysis the group assumed that MicroBooNE will provide a second demonstration of the ability to achieve long electron lifetime in a fully functioning TPC without first evacuating the cryostat. The group assumed that by this time analysis tools will have been developed to reconstruct neutrino events and MicroBooNE physics results are imminent.

Each risk was discussed by the group to reach a consensus determination of the consequence if the event were to occur and likelihood of its occurrence. The risk analysis methodology is an adaptation of a standard technique used for projects; specifically the NSLS-II project. The main elements are risk identification, risk classification, and the presentation of risk mitigation action items (e.g. R&D activities). A section of the risk matrix is shown in Figure 12.1.

The study group proposed the following new R&D activities:

○ A membrane cryostat mechanical prototype to evaluate and gain expertise with this technology.

○ An installation and integration prototype, to understand issues pertaining to detector assembly, particularly in an underground environment.

○ A ~5% scale electronics systems test to understand system-wide issues as well as individual component reliability.

○ A calibration test stand that would consist of a small TPC to be exposed to a test beam for calibration studies, relevant for evaluation of physics sensitivities.

All of these activities fall naturally within the scope of LAr20 project R&D with the exception of the calibration test stand.

The set of residual risks was presented to the LBNE collaboration in October 2009 and to the LAr working group in November 2009 to ensure completeness. A Directors Review of the

R&D plan was conducted in November to consider the completeness of the risk identification and the mitigation plan. The Director's Review committee identified new project risks but did not identify any new technology risks.

12.2   Cryogen Storage Considerations âĂŞ LAr and LN2

FIXME: *New section 6/16/10 from Russ, added but not yet edited by Anne*

FIXME: *Maybe this is supposed to go into vol 6? See email of this date from Russ.*

There is the possibility of using large quantities of liquid argon (on the order of 20,000 tonnes) in lieu of water to capture neutrinos. At this time it is most likely that the liquid argon detector will be located in a new excavation at 800 feet with an egress connection to the DUSEL facility. During filling of the detector, liquid argon will be supplied via pipelines running in a dedicated shaft from the surface. Refrigeration for the argon detector comes from a 50 kW refrigeration system that uses nitrogen (liquid and high pressure gas) as a working fluid. A modest amount (3 days refrigeration), 100 cubic meters, of liquid nitrogen will be stored at the surface as reserve cooling.

While the probability of a cryogenic fluid release is extremely small the consequences are not. The expansion ratio of liquid to gas for argon is in the order of 840 to 1. A release of cryogenic fluids within a confined volume will displace oxygen and cause an oxygen deficiency hazard (ODH). The maximum possible release rate of cryogens will need to be minimized and the ventilation system designed to be able to keep the oxygen concentration at acceptable levels. The large liquid argon inventory for the detector and any intermediate storage tank will be contained in a double walled insulated pit. All transfer lines and ports are located at the top of the tank(s) above the liquid level. With no side wall exposure, a secondary containment membrane within the insulation, and tertiary containment provided by the concrete lined pit, cryogenic liquid release can be limited to the inventory and flow rates of cryogens (liquid argon or liquid nitrogen) within piping sections. While the flow rates of cryogens within those piping lines are significant (on order 600 gpm = 70,000 scfm), the cryogenic transfer lines will be vacuum jacketed (double walled) welded stainless steel piping with negligible probability of failure. Risks associated with cryogenic piping of this sort are comparable to other underground accelerator facilities. A release of gaseous argon from the top of the vessel is limited to (about 300 scfm) the boil off rate of the fluid inventory. Main pressure safety relief valves on the tank(s) or components will be piped to the surface in large diameter dedicated exhaust piping. The area around the vent stack will need to be analyzed and designed for safe mixing and release of inert gas to the atmosphere.

Oxygen depletion sensors shall be installed in area to provide local and remote alarm annunciation in the event of low oxygen levels, see Facility Automation. This is motivated by safety (Oxygen Deficiency Hazard - ODH) and best engineering practices. The ventilation design will incorporate an emergency exhaust system in case of failure. The design is based upon a maximum

1 of one release event yielding a maximum venting of 5,886 CFM [10,000 mÂş/h] based on LNGS,
2 Grand Sasso.

3 12.3 Risk Identification & Mitigation

4   This section presumably will list the risks identified by the LBNE risk identification process
5 (which has yet to be defined) and will describe the mitigation plan.

ID	Risk	Category	Consequence	Likelihood	Likelihood comments	Consequence comments	Risk	Mitigation	Mitigated Likelihood
1	Achievement of adequate lifetime requires evacuation. (MicroBooNE and/or LAPD were not successful)	Argon Purity	3	1	Consensus likelihood is consistent		Med	Keep modular cryostat as an option	0
2	Cannot achieve required drift length	Argon Purity	3	1	e.g. feedthrough leaks, cable outgassing, microscopic cryostat		Med	Develop QA procedures for leak checking (warm & cold) and materials qualification	0
3	Argon purity immediately following filling is poor requiring several volume recirulations before operations can begin	Argon Purity	1	3	We deferred to Flavio's experience on this issue (high likelihood) but the		Med		3
4	Increasing the drift distance is a low impact method of reducing the cost of LAr20, however drift distances >2.5m may not have been demonstrated	Argon Purity	2	1	Long lifetime has been demonstrated, but not long drift distance		Low		1
5	"Hot electrons" at 87K damage the cryogenic ASIC's over the lifetime of the detector with a loss of >50% of the detector channels	Electronics	3	1	There is already in place an R&D plan to address this risk	Revised the risk description	Med	Perform stress test on ~5% of the LAr20 channel count	0
6	Single point failure in electronics requires emptying cryostat to repair	Electronics				Integrated Plan Review comment			
7	The membrane cryostat develops a major leak during operation.	Membrane cryostat	3	0	Ref GEOSTOCK risk assessment < 110k years		Low		0
8	Extrapolation from LNG experience/design to LAr is invalid or not understood adequately	Membrane cryostat	3	1	Consensus likelihood is consistent		Med	Engineering analysis will mitigate this	0
9	Vessel ruptures due to ground water pressure	Cavern	3			Integrated Plan Review comment			
10	Rock freezing causes fracture of supporting rock	Cavern	3			Integrated Plan Review comment			
11	Rock bolt failure cases rupture of cryostat	Cavern	3			Integrated Plan Review comment			
12	Cryostat ruptures due to falling rock	Cavern	3			Integrated Plan Review comment			
13	Suppliers are unable to deliver the needed quantities of cryogens on the schedule needed for filling	Management	2	1	Argon availability is more of an issue in Europe than in the U.S. Stephen: 50kton		Low		1
14	Critical components have a single supplier - procurement & operations	Management	2	0	The CMOS ASIC's are the only critical component that may	Membrane cryostat is the only candidate for single supplier	Low	There is already an R&D plan in place	1
15	There are insufficient technical resources to conduct the planned and proposed R&D	Management	2	3			High	Increase FNAL resources	2

Fig. 12.1. Risk matrix.